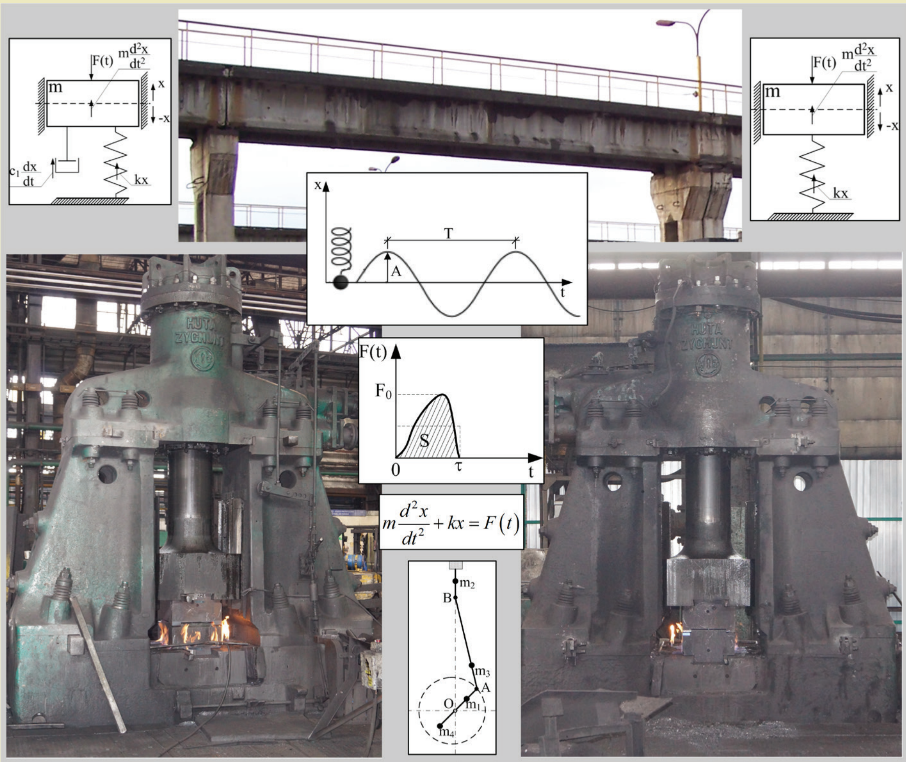
POLITECHNIKA LUBELSKA

Grzegorz Ludwik Golewski

Reinforced Concrete Structures Loaded Dynamically



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Contents

List of Symbols

ϖ	angular frequency of vibrations
λ	angular frequency of natural vibrations
ω	angular frequency of forced vibrations
T	period of vibrations
f	vibrations frequency
A	vibrations amplitude
φ	phase of vibrations
m	mass of the system
$F(t)$	excitation force acting on the system
$m\frac{d^2x}{dt^2}$	inertia force of mass
k	spring stiffness
kx	spring restoring force
c	coefficient of movement resistance
I	impulse
σ_{stat}	sum of stresses caused by a static load
σ_{dyn}	sum of maximum stresses caused by dynamic loads
W_z	fatigue coefficient
f_{dyn}	dynamic deflection
$f_{dyn,per}$	permissible value of dynamic deflection
f_{stat}	static deflection
$f_{stat,per}$	permissible value of static deflection
χ	shock index
S	shock magnitude
A_{per}	permissible amplitudes of forced vibrations
v_{per}	permissible maximum velocity of vibrations
ITZ	Interfacial Transition Zone
σ_{22}^{I}	first critical stress level
σ_{22}^{II}	second critical stress level
σ_{max}	maximum stress cycle
σ_{min}	minimum stress cycle
R	cycle asymmetry coefficient
σ_a	cycle stress amplitude
σ_m	mean cycle stress

$\Delta\sigma$	stress change range
E	modulus of elasticity
ψ	energy absorption coefficient
γ	damping coefficient
f_{fat}	fatigue strength
μ_0	coefficient of stress concentration
α_0	coefficient characterising fatigue strength of the material
f_0	design strength of material for static load
k_0	coefficient of symmetry of stress cycles
S_{st}	generalised characteristic static force
S_{dyn}	amplitude of generalised, design dynamic force
F_α	centrifugal force
M_z	short circuit moment
$F_{\varphi,k}$	characteristic value of the action of the crane
φ_i	dynamic factor
F_k	characteristic value of the static component of the action of the crane

Foreword

Vibrations in buildings and other engineering structures are an integral part of their use. This fact makes the basic knowledge in the area of structural dynamics essential for any Civil Engineering student. It is also required during engineer's professional work.

The purpose of this book is to present the most important issues on the Reinforced Concrete (RC) structural dynamics of RC structures – **with special emphasis on structures loaded in a deterministic manner**.

The book contains a description of the most important structures loaded dynamically. Five chapters in detail present the guidelines regarding: design, construction and maintenance of structures of this type. Furthermore, the most important parameters and characteristics of materials used for the construction of RC structures subjected to dynamic loads are described. The most attention was paid to two largest groups of structures i.e. **foundations for machines** and **crane beams**. The essential part of the book is also information relating to diagnosis and protection of structures from damaging effects of vibrations.

The author also expresses the hope that it can help facilitate the work of future civil engineers, who will encounter in their professional practice the issues relating to the design or construction of RC structures subjected to dynamic influences.

Author

1. Introduction

Various loads of static or dynamic character may act on building structures. Static loads include forces not changing or changing very slowly in time values, directions and points of application with respect to the given object. Dynamic loads are external forces or forces of inertia acting on the object and arising as a result of acceleration of the mass. In addition, dynamic loads may result from massless actions (e.g. wind load arising from air pressure changes).

In practice, building structure design frequently requires taking into account the static and dynamic loads in the calculations. Situations where it is necessary to take into account the occurrence of dynamic influences on structural elements, require a particular attention of the designer due to the fact that the loads of this type cause the occurrence of vibrations in the structure. The vibrations are an inherent phenomenon accompanying buildings throughout their lifecycle, starting from the building process through maintenance up to their disposal, and usually their occurrence does not adversely affect the work of the structure. Exceptions are situations related to the occurrence of:

- the so-called "harmful" vibrations,
- vibrations caused by variable forces, which could cause the occurrence of the so-called "resonance".

The work of structures subjected to the occurrence of "harmful" vibrations or resonant vibrations may in the long term results in very serious effects such as structure's damage or, in extreme cases, failure or destruction. It should be noted, however, that with properly conducted analysis of the structure and proper selection of materials for its construction, the adverse effect of vibrations may be reduced almost entirely.

In the construction of structures exposed to dynamic loads that cause vibrations, materials characterised by sufficient strength, fatigue durability, resistance to external factors (chemical, atmospheric) as well as homogeneity, i.e. identical physical properties throughout its mass are used. The material that meets all these requirements is undoubtedly **Reinforced Concrete (RC)**. Therefore, it is an essential and widely used construction material for dynamic load-bearing structures.

2. Introduction to building dynamics

2.1. Basic definitions, terms and formulas of applied dynamics

Dynamics is the branch of mechanics, which deals with the motion of macroscopic bodies and with the reasons for motion. During the motion of these bodies, mass inertia forces and movement resistance occur in addition to forces of gravity.

Building Dynamics relate to the motion of building structures, which in practice comes down to the description and analysis of vibrational motion. Entire structures or their components such as beams, slabs, shells, foundations can be subject to vibrations. The objective of building dynamics is to determine the reaction (called a structure's response), i.e. displacements and stresses for a given type of building structure subjected to any dynamic load.

The vibrational motion, commonly referred to as **oscillations** or **vibrations** is a process, in which the physical quantities are variable as a function of time. With regard to building dynamics, it is a movement, in which the tested coordinate describing the building position, oscillates around its equilibrium level. The analyzed values (e.g. displacement values) move toward the established state of equilibrium and away from it.

Dynamic loads are all forces acting on the structure, which are characterised by variability in a short period of time in relation to the essential dynamic characteristics (a period of natural vibrations) of the loaded structure. The dynamic loads do not include loads whose variability in time is slow and lasts for hours, months or even years (e.g. rheological changes). Changes in parameters of dynamic load can be mechanical (e.g.: force, pressure, stress, strain, displacement) but also thermal, electrical and chemical. A detailed breakdown of types of dynamic loads is presented in Ch. 2.5.

Basic terms of the vibrations theory are derived from the description of a simple harmonic motion. Also, in most of the structures, in which dynamic loads occur (e.g. foundations for machinery), the excitation forces cause the occurrence of **harmonic oscillations**.

Harmonic motion is a motion of a point moving on a circle with the uniform motion on the diameter of the circle (Fig. 2.1.). A constant angular velocity of such motion, also known as the **angular frequency**, is denoted with the symbol ϖ. Full rotation of a point, in other words course of an angle 2π, requires time T – of so called **period of vibrations**, while the number of vibration cycles in the time unit is **vibration frequency** f. Motion of the point on the diameter gives the sinusoidal (or cosinusoidal) graph. If the radius of the circle is A, then values $\pm A$ on the graph are the greatest deviations from the central position. A is called the **vibration amplitude**. The angle φ from which the entire course starts is called the phase angle or **phase of vibrations**. Tab. 2.1 summarises all the important parameters describing harmonic vibrations along with their units, while the scheme of the simple harmonic motion is shown in Fig. 2.1.

Tab. 2.1. Parameters describing harmonic vibration

Parameter	Unit
Angular frequency of vibrations – ϖ	[rad/s]
Period of vibrations – T	[s]
Vibrations frequency – f	[Hz]
Vibrations amplitude – A	[m]
Phase of vibrations – φ	[rad]

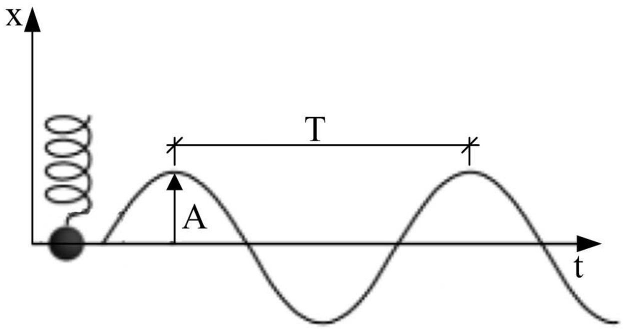


Fig. 2.1. Scheme of simple harmonic motion (described in text)

Among parameters in Tab. 2.1., the following relationships occur.

$$T = \frac{2\pi}{\varpi}, \ \varpi = 2\pi f, \ f = \frac{1}{T}. \quad (2.1)$$

Geometrically, harmonic motion is described as a simple wave motion with the equation of:

- displacement:

$$s = A \sin \varpi t, \quad (2.2)$$

- velocity:

$$\frac{ds}{dt} = \dot{s} = \varpi A \cos \varpi t, \quad (2.3)$$

- acceleration:

$$\frac{d^2 s}{dt^2} = \ddot{s} = -\varpi^2 A \sin \varpi t, \quad (2.4)$$

where: t – time [s].

Due to the repeatability of vibrations, they can be divided into: **repetitive** and **non-repetitive**. In building practice, vibrations from the first group occur more frequently. They include vibrations: **periodic** (including harmonic), **non-periodic** and **quasi-periodic**. Periodic vibrations (Fig. 2.2.a) are vibrations with the repetitive course at a fixed time interval (period of vibrations) – *T*. All other vibrations that do not meet this condition are non-periodic (Fig. 2.2.c). Vibrations close to periodic vibrations, with approximation characterised by a certain repetition, are called quasi-periodic (Fig. 2.2.b).

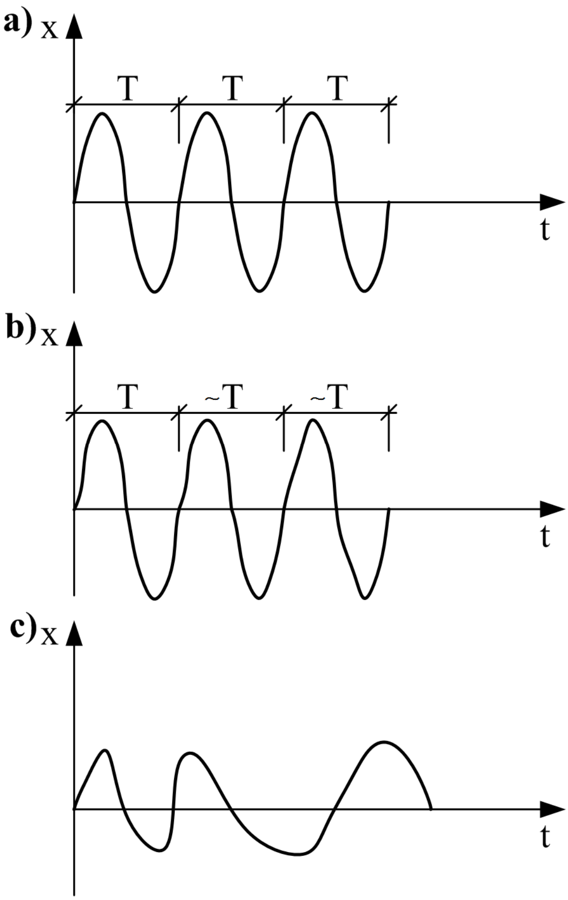


Fig. 2.2. Graphs of vibrations: a) periodic, b) quasi-periodic, c) non-periodic

Short-term, sudden and momentary loads, most often in the form of impulses, belong to the second group – non-repetitive vibrations. The summary of all types of vibrations, depending on the variation in time, is shown in Fig. 2.3.

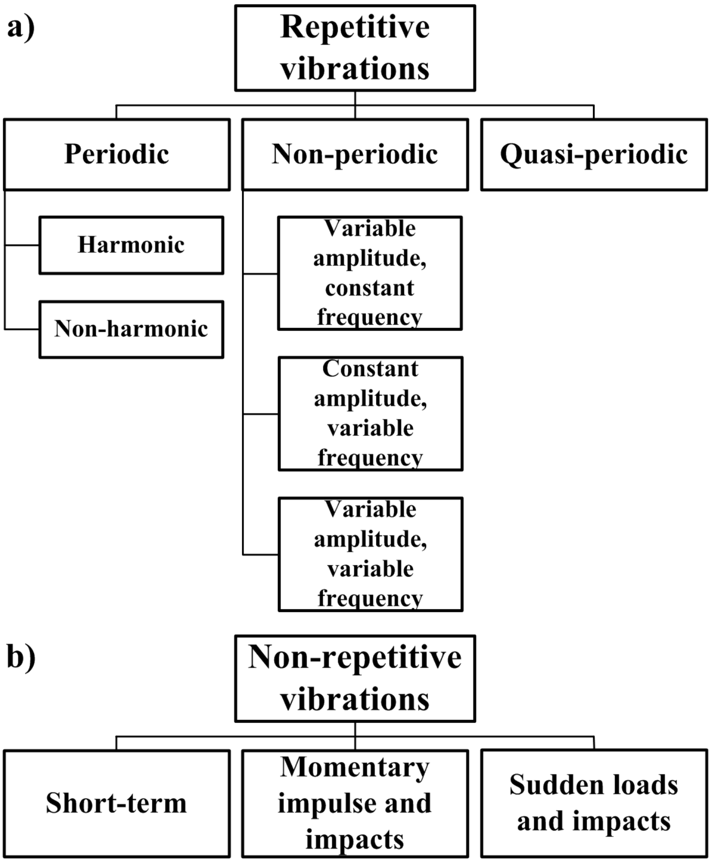


Fig. 2.3. Breakdown of vibrations depending on the variation in time: a) repetitive vibrations, b) non-repetitive vibrations

Natural vibrations, also called free vibrations, are vibrations characteristic of a given structure. Their physical image is obtained after activation of a single, short impulse.

Forced vibrations in the system occur due to external forces. Depending on those external forces, the following vibrations are distinguished:

- **flexural transverse vibrations** – if bending occurs,
- **torsional vibrations** – if torsion occurs,
- **shear vibrations** – if shearing occurs,
- **longitudinal vibrations** – if compression or tension occurs.

The equation or graph describing the motion of the building during vibrations is called a **form of vibrations**. The vibrations excited in the source propagate with the wave motion through the centre (soil, structures) as waves. Then, they reach the object that receives these vibrations and responds with its own vibrations.

Due to the type of generation, **longitudinal** and **transverse waves** (shear), **longitudinal surface waves (Rayleigh) and transverse surface waves (Love)** are distinguished.

Dynamic scheme of the building system is a static scheme supplemented with information essential from the dynamics point of view. This information includes: mass description and distribution, movement resistance types and distribution as well as description of external excitation forces as a function of location and time. The state of displacement of mass points belonging to the relevant system can be described by a set of information, called generalised coordinates. Number of independent generalized coordinates necessary to determine the positions of all mass points at a given time with respect to the state of static equilibrium is called the number of dynamic degrees of freedom. From the point of view of the number of dynamic degrees of freedom, the following breakdown is introduced:

- **systems with one degree of freedom**,
- **systems with finite number of degrees of freedom** (discrete systems),
- **systems with infinite number of degrees of freedom** (continuous systems).

All relationships below – for undamped and damped vibrations – will concern the system with one degree of freedom.

2.2. Undamped vibrations of system with one degree of freedom

Natural vibrations are the simplest type of vibrations and characterise a given body in terms of dynamics. In this type of vibrations, due to the excitation force – $F(t)$, a point deflects from the equilibrium position as schematically shown in Fig. 2.4.

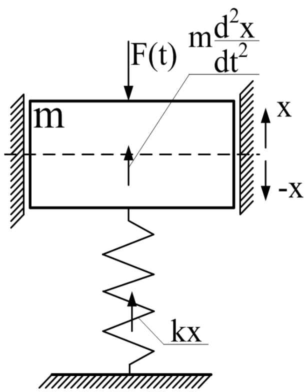


Fig. 2.4. Diagram of the vibrating system with one degree of freedom (described in text)

The following summarises the equations and basic relationships for undamped natural vibrations:

a) general equation of undamped vibrations (Fig. 2.4) excited by force applied to the mass:

$$m\frac{d^2x}{dt^2}+kx=F\left(t\right) \tag{2.5}$$

where: m – mass of the system [kg], $m\frac{d^2x}{dt^2}$ – inertia force of mass [kN], k – spring stiffness [kN/m], kx – spring restoring force [kN], $F\left(t\right)$ – excitation force acting on the system,

b) equations of vibrations without damping so called natural vibrations:

$$\frac{d^2x}{dt^2}+\lambda^2x=0, \tag{2.6}$$

where: λ – angular frequency of natural vibrations [rad/s], $\lambda=\sqrt{\frac{k}{m}}$.

Often RC structures loaded dynamically may be subject to **forced vibrations**. Such a situation occurs, for example in the foundations for machines. The excitation of these vibrations can be done in two ways:

- through vibrations excitement with harmonic force,
- through vibrations excitement with harmonic movement of the ground.

Below are the equations and relationships for undamped forced vibrations.

a) equation of undamped forced vibrations excited with harmonic force – $F=F_0\sin\omega t$:

$$\frac{d^2x}{dt^2}+\lambda^2x=\frac{F}{m}, \tag{2.7}$$

b) equation of undamped forced vibrations excited with harmonic motion of the ground – $u=u_0\sin\omega t$:

$$\frac{d^2x}{dt^2}+\lambda^2\left(x-u\right)=0, \tag{2.8}$$

where: ω – angular frequency of forced vibrations [rad/s].

2.3. Damped vibrations of system with one degree of freedom

In some RC structures loaded dynamically, vibrations may adversely affect the structure itself as well as the plant and machinery operating in the vicinity of the source of vibrations. The vibrations can also be felt by humans in the influence zone. These problems will be discussed in Ch. 2.6.

To minimise adverse effects of dynamic loads, actions are undertaken to minimise the occurrence of vibrations. Furthermore, vibrations can be damped by the surrounding environment. A typical example may be the ground under foundations, on which the machines generating vibrations are placed. The ground located at the level of foundation is able to damp the effects of machine operation and its behaviour can be modelled as that of a viscous liquid.

Damping enables energy to be dissipated from external forces and is inextricably connected with movement of the structure. The ability of damping is determined as the ratio of energy dissipated in one vibration cycle to the total energy introduced to the system. Damping is divided into:

- internal – material or structural,
- external – environmental.

The essential information on how to damp vibrations for machines with the greatest dynamism of work, will be presented in Ch. 4.8. Below is the classification of some types of damping.

a) **material damping –** mainly dependent on the viscoelastic behaviour of the material of which the structure is made, but also on friction in the cracks formed in concrete. It is also known as internal friction. It directly depends on the internal structure of the vibrating body. Energy dissipation results from the relationship between molecules, the type of material, construction methods, final finish, temperature and the effort of the structure. The phenomenon of material damping occurs in crystals, involving movements of atoms with respect to each other in the crystal grid, energy dissipation in the intercrystalline layer, and dislocation slips.

b) **structural damping** – is friction in connections and supports. In elements connected in a rigid manner, as a result of elastic deformations, a slip occurs at the border of contacting surfaces. Dry friction occurs at the interface of movable connections, when there is no lubrication in the connection. Viscous friction occurs if there is lubrication. Structural damping has a big impact on the reduction of vibrations and depends on the static scheme, the dimensions of the structure and the elements such as railings or lanterns (e.g. in viaducts and bridges).

c) **external environmental damping** – the damping factors, the source of which is the surrounding environment, include vehicles on viaducts and bridges; pedestrians on footbridges; ground, water and wind resistance.

According to Lewandowski (2014), currently, vibration reduction (damping) systems – in which dynamically loaded structures are equipped – are used in order to:

- reduce vibrations caused by earthquakes and thus reduce their devastating consequences,
- increase the comfort of occupants in high buildings susceptible to wind action,
- increase the service comfort of viaducts, bridges and footbridges when the frequencies of natural vibrations are similar to the frequencies of excitation forces, caused by moving vehicles or pedestrians,
- prolong the lifecycle of the structure in spite of material fatigue,
- reduce or eliminate vortex-induced vibrations, e.g. in RC chimneys.

Equations and formulas of damped natural and forced vibrations of the system with one degree of freedom are summarised in the following formulas and in Fig. 2.5 and 2.6. The characteristic feature of this type of vibrations, which can be seen in Fig. 2.6, is a clearly decreasing vibrations amplitude.
Detailed solutions of both equations regarding undamped and damped vibrations can be found in Chmielewski, Zembaty (1998).

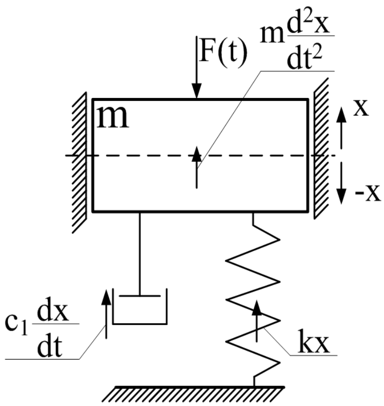


Fig. 2.5. Diagram of the vibrating system with one degree of freedom with damping (described in text)

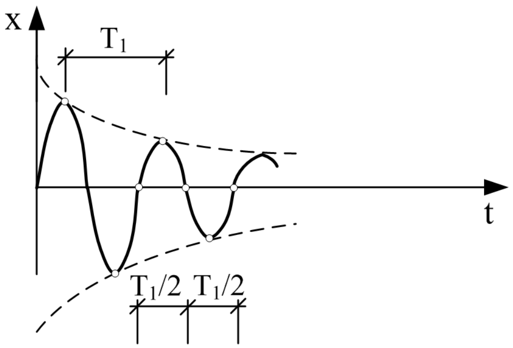


Fig. 2.6. Characteristics of damped harmonic vibrations; T1 – period of damped vibrations

a) general equation of damped vibrations:

$$m\frac{d^2x}{dt^2}+c_1\frac{dx}{dt}+kx=F(t), \qquad (2.9)$$

where: $c_1\frac{dx}{dt}$ – force of viscous movement resistance proportional to velocity [kN],
k – as in formula 2.5,

b) equation of damped natural vibrations

$$\frac{d^2x}{dt^2}+2c\frac{dx}{dt}+\lambda^2x=0, \qquad (2.10)$$

where: $c=\frac{c_1}{2m}$ – coefficient of movement resistance [1/s], λ – as in formula 2.6,

c) equation of forced damped vibrations excited with the harmonic force – $F=F_0\sin\omega t$:

$$\frac{d^2x}{dt^2}+2c\frac{dx}{dt}+\lambda^2x=\frac{F}{m}, \qquad (2.11)$$

where: c , λ , ω – as in formulas above,

d) equation of forced damped vibrations excited with harmonic motion of the ground – $u=u_0\sin\omega t$:

$$\frac{d^2x}{dt^2}+2c\left(\frac{dx}{dt}-\frac{du}{dt}\right)+k(x-u)=0, \qquad (2.12)$$

where: c , k – as in formulas above.

2.4. Impulse operation

Another form of dynamic loads acting on the reinforced concrete structures can be generated in the form of impulses. **Impulse *I*** – is a load with maximum value F_o, acting on the structural arrangement for a short time interval – τ. In practice, this type of load is generated by impact machines such as forging hammers. The magnitude of impulse is defined as the integral (the hatched area of the field in Fig. 2.7.) given with the formula 2.13.

$$I = \int_0^{\tau} F(t)\,dt = F_o \int_0^{\tau} f(t)\,dt = F_{sr}\tau \qquad (2.13)$$

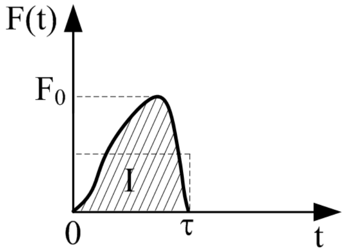


Fig. 2.7. The course of impulse in time (described in text)

Loads are treated as impulse loads, if the impulse duration τ satisfies the condition:

$$\tau \le 2{,}5T_{w1}, \qquad (2.14)$$

where: T_{w1} – basic period of vibrations in the system on which the load acts.

If the above condition is not satisfied, it can be assumed that a static load occurs. The value of this load, used in the calculations, must, however, be increased by a coefficient κ which, depending on the impulse form, ranges from 1.1 to 2.0.

For practical purposes, two types of impulse loads are distinguished, i.e.:

- **sudden impulse**, when $\tau < 0{,}1T_{wn}$,
- **short-term impulse**, when $0{,}1T_{wn} \le \tau \le T_{w1}$,

where: T_{w1} – largest (basic) period of vibrations of the system, T_{wn} – the smallest period of natural vibrations.

2.5. Types of dynamic loads

2.5.1. Origins and classification of external loads

Dynamic loads acting on engineering structures may come either from the force of nature such as wind load, earthquakes, sea waves; or from the industrial or technical human activity such as vehicle traffic on bridges and viaducts or movement of crane beams; from some machine parts during rotational or reciprocating motion; from the impacts of hammer; from the explosions in the air or in the ground (during works in quarries); from the shocks caused by the exploitation of coal deposits or during transport by road and rail (Kappos 2002). A detailed breakdown of dynamic loads will be presented later in this chapter.

Energy from the dynamic loads can be transferred directly to the structure through any center, which can be:

- solids (structural elements, running machines),
- gas (usually air),
- liquids (usually water).

In some cases, there are also indirect means of energy transfer, which most commonly are:

- movement of the ground during earthquakes,
- ground movement from the road or rail transport.

Time-dependent dynamic loads are defined as **excitation forces**. All excitation forces, causing vibrations of the structure, can be divided into **deterministic** and **non-deterministic** forces.

Deterministic forces include those which can be described with the help of strict mathematical relationships, e.g. centrifugal force generated by the operation of rotating machinery.

Non-deterministic forces are all physical phenomena which produce excitation forces acting on structures and are random, e.g. wind speed, ground acceleration during earthquakes, etc. Such loads are inherently random and cannot be described by strict functional dependencies, but only by using statistics. The breakdown of deterministic and random excitation forces is compiled on the basis of work Chmielewski, Zembaty (1998), in Fig. 2.8.

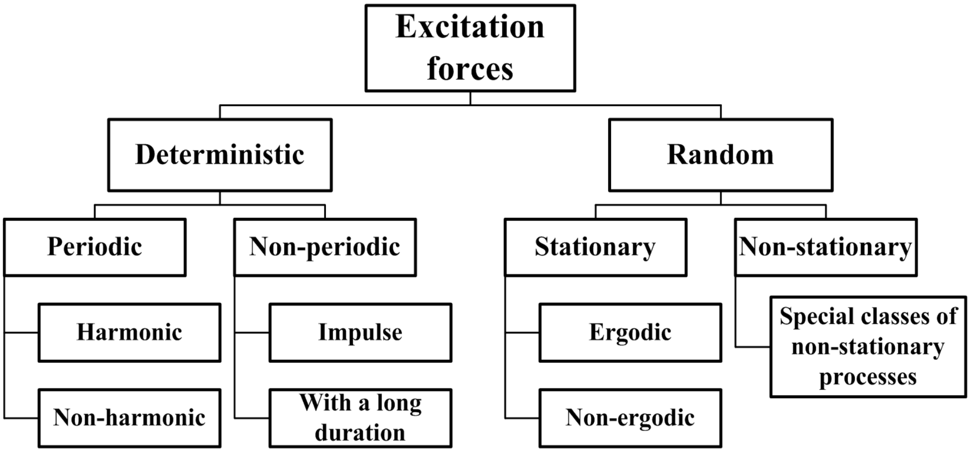


Fig. 2.8. Characteristic of exitation forces resulting in structure's vibrations (Cmielewski, Zembaty 1998)

2.5.2. Distribution of dynamic loads

The number and variety of dynamic loads acting on buildings and caused by both human activities and factors independent of human activity are significant (Kappos 2002). Therefore, several criteria can be identified in the scope of building construction dynamics, mutually interpenetrating and complementing, based on which the breakdown takes place.

Dynamic influences in the civil engineering industry are conventionally divided into:

a) **natural –** independent of man, resulting from forces of nature. Such forces are transferred to the building through the ground or air in the form of wave and they constitute a kinetic extortion. These are, therefore, rapid changes in the air pressure (wind action) or ground movements (seismic actions).
b) **civilization** – resulting from intentional human activity. These are forces depending on humans, but they are not always under their control. Such loads are transferred similarly as in the case of natural influences through the air and ground.
c) **occurring inside buildings –** normally associated with the operation of machines and equipment. This group includes forces which may cause motion excitation of structural elements, e.g. ceilings, walls, foundations or other building's components. The source of these loads can be clearly located and fully identified (e.g. fan installed inside the building) or accidental and not always precisely known (e.g. vibrations from the operation of the installation or caused by moving people in the building).

Depending on the source, vibrations can be divided into:

a) **seismic –** caused by rapid earth movements (earthquakes), which propagate from the inside of the earth to the surface and then disperse over it,
b) **paraseismic –** caused by human dependent sources.

The vibrations of paraseismic origin received by buildings and people are divided depending on:

a) the origin:
- vibrations excited for the technological, technical-utilitarian and therapeutic uses,
- vibrations that are a side effect of various targeted actions,

b) method of excitation:
- dependent and controlled or operated by humans,
- dependent, but controlled only partially and indirectly by humans,
- dependent, but not controlled by humans,

c) continuity and course of excitement:
- continuous and regular,
- continuous, but irregular,
- short-term with a regular repeating course at certain time intervals,
- short-term, irregularly repetitive with varying course,
- single-use,

d) source position in relation to the building:
- outside the building,
- inside the building transferred indirectly (e.g. by separate foundation),
- inside the building transferred directly (e.g. on the ceiling).

A detailed classification of dynamic loads can be based on the analyses of vibration pathways to a building. There are distinguished:

a) **paraseismic loads**, the source of which are:
- pedestrian footfall which has a particularly adverse effect when the movement of a large group of people is synchronised (e.g. the march of a military column on the bridge or viaduct); this leads to the structure resonance,
- communication shocks from motor, rail (rail, tram) and special vehicles (e.g. tanks, conveyors),
- communication shocks caused by movement of underground vehicles (e.g. underground railway),
- vibrations caused by work of overhead cranes, hoists and hoisting winches,
- operation of personal lifts in buildings,
- vibrations and shocks caused by the use of technology shocks in technological processes associated with ground (e.g. pile driving, vibro displacement, vibroflotation),

- shocks from explosions or technological impacts on the surface (construction works, pile driver impacts, operation of vibrohammers, technological explosions),
- shocks transferred through the ground from the foundations of technological devices in the industry (e.g. operation of die forging hammers),
- fall of heavy objects (e.g. a plane crash),
- shocks caused directly or indirectly by mining exploitation both underground and open pit (e.g. excavation pits),
- shocks caused by violation of the substrate or emergency explosions in the substrate (e.g. gas pipeline),
- substrate shocks due to natural or artificial changes in hydrogeological or geotechnical conditions in the substrate,
- high power bullet explosions (e.g. bombs, rockets),

b) **shocks transferred through the air** (outside a building), as follows:
- all forms of dynamic effect of wind (longitudinal load, transverse load, galloping),
- air shock waves (gusts) from bullet explosions (bombs),
- loads with the impact wave caused by passing supersonic aircraft,
- other sources of vibrations from artificially generated acoustic wave (e.g. operation of bells),

c) **shocks with sources inside buildings,** which include:
- additional installations of production or service devices,
- explosion of gaseous substances indoor or in internal cables,
- operation of acoustic wave generated inside the building (e.g. sound effects during the emission of a movie in the cinemas),
- shocks from falling objects in buildings.

2.6. Dynamic diagnostics and protection against harmful effects of vibrations

2.6.1. Dynamic diagnostics and related procedures

Diagnostics means all activities and factors needed for diagnosis. In diagnostics, it is important not only to describe the condition, but also the reasons for its occurrence. In connection with this, diagnostics refers to the cause-effect activities during which an expert answers the question: is there a cause-effect relationship between influences and technical condition of the object ? If dynamic interactions occur among the analysed impacts, such diagnostics is defined as **dynamic diagnostics**.

The basic objectives of dynamic diagnostics are:

- to determine dynamic characteristics of the object,
- to state that certain designated boundaries are not exceeded, e.g. dynamic displacements; or to state that specific dynamic effects did not occur, e.g. resonance,
- to determine the damages to the object caused by dynamic loads.

Cause-effect dynamic diagnostics can be further combined with an indication of how the situation of the object changes, e.g.: load limitation, repair damage, structural changes of the object, installation of protective devices.

The range of diagnostic procedures and related tasks can be summarised in the following order:

- to collect data about the vibration source whose impacts on the object may be significant,
- to collect data about the route of vibration propagation from the source to the object receiving vibrations,
- to collect data about the object receiving vibrations and its technical condition,
- the acceptance of criteria for assessment of the vibrations influence on the object,
- to determine parameters describing the reaction of the object receiving vibrations,
- the assessment of vibrations influence on the object,
- the comparison of the results of the assessment with the condition of the object receiving vibrations,
- to answer the question whether there is a cause-effect relationship between the action of vibrations source and the condition of the object receiving vibrations.

In the case of such relationship, the author of diagnosis should propose technical measures, the use of which would lead to a corresponding reduction in dynamic actions on the object. If the condition of the object indicates a need for repair or reinforcement, the development of a method to perform this task is in the scope of works covered by diagnosis.

In addition to dynamic diagnostics of existing buildings, there are also diagnostic studies regarding the forecast situations that may occur in the future. Such studies are more forecasts than diagnosis of the condition of existing situation, which makes the course of conduct in such situations different at some points from the typical diagnostic scheme. Subsequent steps of the diagnostic procedure relating to the building in the forecast situation are as follows:

- to collect data about the designed building,
- to collect data about the designed sources of vibrations,
- to determine forecast dynamic characteristics of the building,
- to determine forecast parameters of ground's vibrations in the location of a building,
- to determine the response of the designed building to forecast vibrations,

- to assess the vibrations influence on the object receiving vibrations with the use of accepted diagnostic criteria,
- to give results of the diagnosis regarding the need to reduce response of the structure to dynamic action,
- to propose – or if needed to reduce the projected response – technical measures required to achieve the desired objective,
- to verify the results of diagnosis (conducted experimentally) after the building is constructed and after the source of vibrations is installed.

In the given above general schemes of diagnostic procedures of the building – in the existing and forecast situation – an **object receiving vibrations** can be:

- a structure (including, in particular, a building),
- a human in the building,
- a vibration sensitive device located in the building.

In respect to all three types of the object receiving vibrations, the determination of vibration parameters in specific points is required. The choice of these locations and the designated expressions of the building's response to vibrations depend on the evaluation criteria in the diagnosis.

2.6.2. Conditions for buildings receiving vibrations

In building diagnostics, the following four conditions should be satisfied: strength, stiffness, structure and technology. Details relating to each of the above-mentioned conditions are presented in the following sections:

a) dynamic strength conditions

This boundary condition and stiffness condition are the most important criteria that should be strictly satisfied in the course of diagnostics of a dynamic structure. The strength condition – given in the formula 2.15 – should be checked in the most adverse cross-sections and for the presence of stress concentration effect

$$\sigma_z = \sigma_{stat} + \sigma_{dod} \leq k^{'}, \quad (2.15)$$

where: $\sigma_{dod} = \sigma_{dyn} \cdot W_z$, (2.16)

σ_{stat} – sum of stresses caused by a static load, σ_{dyn} – sum of maximum stresses caused by dynamic loads, $k^{'}$ – allowable stress at the static load of the same type, W_z – fatigue coefficient, dependent on the fatigue strength and characteristics of the cycle of vibration repeatability, ranging from 1.0 to 4.0.

b) stiffness conditions

This condition is usually given as the maximum allowable amplitude of vibrations (dynamic displacements) or as maximum total displacement. In practice, values of permissible amplitude of vertical vibrations of ceiling elements depend on the values of permissible static deflections. In the case of a dynamic source of vibrations, the following conditions should be satisfied:

$$f_{dyn} \le f_{dyn,per}, \tag{2.17}$$

$$f_{stat} + f_{dyn} \le f_{stat,per}. \tag{2.18}$$

In the case of stationary and long-term vibrations, it is essential to take into account the fatigue effect. In this case, the relationship represented with the formula 2.19 should be checked

$$f_{stat} + f_{dyn} \cdot W_z \le f_{stat,per}, \tag{2.19}$$

where: f_{dyn} – dynamic deflection, $f_{dyn,per}$ – permissible value of dynamic deflection, f_{stat} – static deflection, $f_{stat,per}$ – permissible value of static deflection,

c) structural conditions

Structural conditions supplement conditions resulting from serviceability requirements. These include: conditions of the limited crack openings, impermeability condition, condition of tensile stress absence, condition of not exceeding expansion joints openings, condition of cracks or flaking plaster. These conditions are formulated for specific types of structures or entire classes of structures. To a large extent, they depend on the material and adhesives used.

d) technological conditions

Technological conditions are associated with the possibility of proper exploitation of a building and devices installed in it. Physiological conditions of vibrations on people could also be included in these conditions, if they are users of the building. Technological conditions are usually formulated in the form of allowable single maximum amplitudes of displacements, velocities or accelerations, to which a building or its part can be exposed during vibrations. These conditions should be determined by the occupant or the supplier of the device. In the absence of such information, they can be determined based on divisions given in tables in Chapters 2.6.3 to 2.6.5.

In addition, a very important criterion, which should be strictly complied with, is the protection of building structures and machines prior to the occurrence of **resonance**. Such situation may occur when frequency of natural vibrations of the object λ and frequency of forced vibrations ω will have the same or very similar values. Therefore, it is required that the following condition is satisfied

$$\lambda \neq \omega. \tag{2.20}$$

2.6.3. Criteria for assessment of vibration influence on buildings

a) types of damages in buildings caused by vibrations

Harmful vibration effects may cause damages in buildings. These can be of two types: **non-structural damages** and **structural damages** (i.e. damages of load-bearing elements).

Non-structural damages include: scratches and cracks of coating and plasters, loosening of door and window fasteners in walls, ceramic wall tiles falling off, scratches and cracks of partition walls, etc. Damages to load-bearing elements include damages which lead to strength reduction of structural elements of buildings, e.g.: cracks and scratches of supporting walls, connections of walls, lintels, pillars, etc.

In order to protect buildings from the vibration influences - which could result in damage to its structural elements, or architectural damage – special scales of dynamic effects have been developed. The risks caused by adverse effects of vibrations can also be assessed based on parameters of the shock and magnitude indicators.

b) assessment of vibration influence on buildings based on scales of effects of dynamic influences

The easiest way to assess the degree of harmfulness of vibrations and shocks on buildings is to read special scales of the predicted effect for measured or predicted vibrations of the building. The parameters required to determine the degree of risk of the structure (for a given type of scale) are most frequently values of accelerations or velocities of vibrations, or – as it was recognised in the Zeller scale – a combination of accelerations and frequencies of vibrations. Currently, two basic scales that assess the degree of harmfulness of vibrations are scales based on **shock index** – χ or **shock magnitude** – S. Formulas for determining the value of both parameters are listed below:

$$\chi = \frac{b^2}{n}, \tag{2.21}$$

$$S = 10\log\frac{\chi}{\chi_0}, \tag{2.22}$$

where: χ – shock index [cm^2/s^3], b – acceleration amplitude [cm/s^2], n – vibration frequency [s^{-1}], S – magnitude of shock [vibrary], χ_0 – index of reference shock [0.1 cm^2/s^3].

Table 2.2 presents the assessment of effects of dynamic influences on buildings, depending on the shock index in compliance with Zeller's scale, and in Tab. 2.3 depending on the magnitude of shock in compliance with the vibrary scale. It should be added that both scales give only a very general interpretation of effects of vibrations on buildings and are generally used as the first manifestation in this type of hazards. This situation results from neglecting the vibration and shock influences on buildings in these scales: characteristics of the building itself (type of structure, material from which it is made, building maintenance), type of substrate and other significant features that determine the strength of the structure. This often results in differences in the assessment of the vibration effects depending on the adopted scale. Problems of this type were sought to be eliminated – by developing the so-called dynamic effects scale (DES) – included in the Polish standard PN-85/B-02170 (1985). Its characteristics and rules of application are discussed in subparagraph c.

Tab. 2.2. Assessment of effects of dynamic influences on buildings, depending on the shock index in compliance with Zeller scale

Degree	Characteristics of vibrations and risks of the structure	Shock index χ [cm^2/s^3]
I	Undetectable	1÷2
II	Very weak	2÷10
III	Weak – first cracks on plasters and coating may appear	10÷50
IV	Average – cracks on plasters appear, cracks of walls may appear	50÷250
V	Fairly strong – cracks and scratches of walls, plasters flake	250÷1000
VI	Strong – cracks of walls and reinforced concrete structures, cornices may fall off	1000÷5000
VII	Very strong – buildings endangered, beams, lintels may fall off, etc.	5000÷20000
VIII	Extremely strong – indirect threat to stability of structural elements of buildings at constant vibrations	20000÷100000

Tab. 2.3. Assessment of effects of dynamic influences on buildings, depending on the magnitude of shock in accordance with the vibrary scale

Degree	Characteristics of vibrations and risks of the structure	Magnitude of shock S [vibrary]
I	Shocks unnoticeable in buildings	1÷2
II	Weak shocks without substantial damages to buildings	2÷10
III	Average shocks without substantial damages to buildings, first cracks and scratches	10÷50
IV	Fairly strong shocks – damages to the building occur, cracks and scratches of walls, coating falls off	50÷250
V	Strong shocks – extensive damages to the building, scratches of load-bearing walls, ceilings, threat to the stability of buildings	250÷1000
VI	Very strong shocks – failure, possibility of total destruction of some buildings	1000÷5000

c) assessment of vibrations influence on buildings based on DES scales

The main claim underlying the preparation of DES scales was the assumption that the use of scales makes sense only in relation to the most common one- or several-storey buildings that are made of brick or mixed structure. In such cases, while relying on a model of the building, some type of nomograms classifying the effects of dynamic impacts on buildings can be developed. In addition, the preparation of nomograms should take into account the existing conditions such as:

- various structural types of buildings,
- various types of substrates on which the buildings are constructed,
- various types of vibration waveforms,
- criteria of damage, which are based either on the stress limit values or the limit strain.

DES scales, included in standard PN-85/B-02170, are divided, depending on the shape and dimensions of buildings, into two groups: **DES-I** scale, shown in Fig. 2.9., is only for compact buildings with the horizontal projection of small size (up to 15 m), with one- or two-storeys and with the height not exceeding any of the dimensions of horizontal projection. **DES-II** scale, shown in Fig. 2.10., refers to buildings not higher than five storeys, the height of which is less than twice the minimum width of the building and low buildings (up to two storeys), but not satisfying the conditions specified for DES-I scale.

DES scales have five zones (I, II, III, IV and V) separated by four limit lines (A, B, C, D). These lines are given in Fig 2.9.a and 2.10.a in the coordinate system: vibration frequency (f) – displacement (d), and in Fig. 2.9.b and 2.10.b in the coordinate system: vibration frequency (f) – acceleration (a).

The following criteria of breakdown into hazard zones (PN-85/B-02170 1985):

zone I – vibrations unnoticeable in buildings,

boundary A – lower limit of vibration perceptibility in buildings and lower limit of dynamic influences; with vibrations below this limit, dynamic influences can be considered negligible,

zone II – vibrations noticeable in buildings, but harmless for the structure; accelerated fatigue of the building and first cracks in the coatings, plasters, etc.,

boundary B – stiffness limit of a building, lower limit of cracks and scratches in structural elements; dynamic influences below this limit do not cause adverse effects in the building,

zone III – vibrations harmful for the building, which cause local scratches and cracks, thus weaken the building structure and reduce its load capacity and resistance to further dynamic influences; coating and plasters may fall off,

boundary C – limit strength of individual elements of the building, lower limit of heavy structural damages,

zone IV – vibrations of high harmfulness for the building and posing a risk to the safety of its residents, numerous cracks, local destruction of walls and other individual elements of the building; suspended objects fall off, ceilings fall down, movement of the floor beams from the bearings, etc.; it is required to remove the source of vibrations or weaken its influence as quickly as possible,

boundary D – limit structure stability, lower limit of the failure of an entire building; vibrations above this limit may cause the failure of the building and threaten the safety of human life,

zone V – vibrations make the building walls collapse, ceilings fall down, etc., full safety hazard to human life; in the case of vibration occurrence risk, this type of building must not be used.

The boundaries of zones shown in Fig. 2.9 and 2.10 are given in two variants: according to the assessment of the building, type of substrate and type of vibrations. Assigning to the respective variant is followed by the vast majority of relevant characteristics listed in Tab. 2.4. In the case of short-term vibrations and in the case of fulfilment of all conditions listed in the third column of Tab. 2.4, the increase in the boundaries of zones is permitted when checking the harmfulness of vibrations in a building (e.g. vibrations with parameters in zone II, under the given conditions, can be attributed to the effects for zone I).

Tab. 2.4. Characteristics of buildings used to determine the boundary of vibration hazard zones

Evaluation by	Characteristics of boundaries	
	Lower (continuous line in Fig. 2.9. and 2.10.)	Higher (dashed line in Fig. 2.9 and 2.10).
Condition of building	Old buildings, with damages, renovated or reinforced buildings	Buildings not damaged, without structural modifications
Materials and structure of building	Masonry, slag concrete, stone buildings, of negligent construction, lack of foundations, no ring beams, vaulted ceilings, large holes in walls or irregular holes	Walls of solid bricks carefully constructed, reinforced concrete or concrete foundations, massive ceilings connecting walls with a ceiling ring beam
Type of substrate and method of foundation	The substrate with low stiffness (e.g. silty, loose sands), discontinuous (different heights) or intermediate foundation	Rigid substrate (e.g. silts and hard-plastic clay), flat foundation
Type of vibrations	Long-term or permanent vibrations	Short-term vibrations

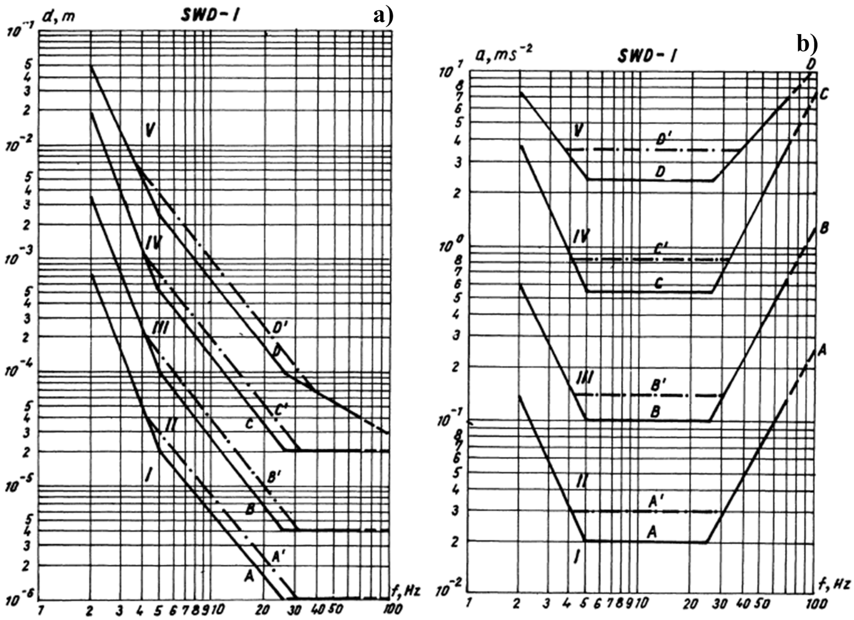


Fig. 2.9. Scale of dynamic influence on buildings DES-I (PN-85/B-02170 1985)

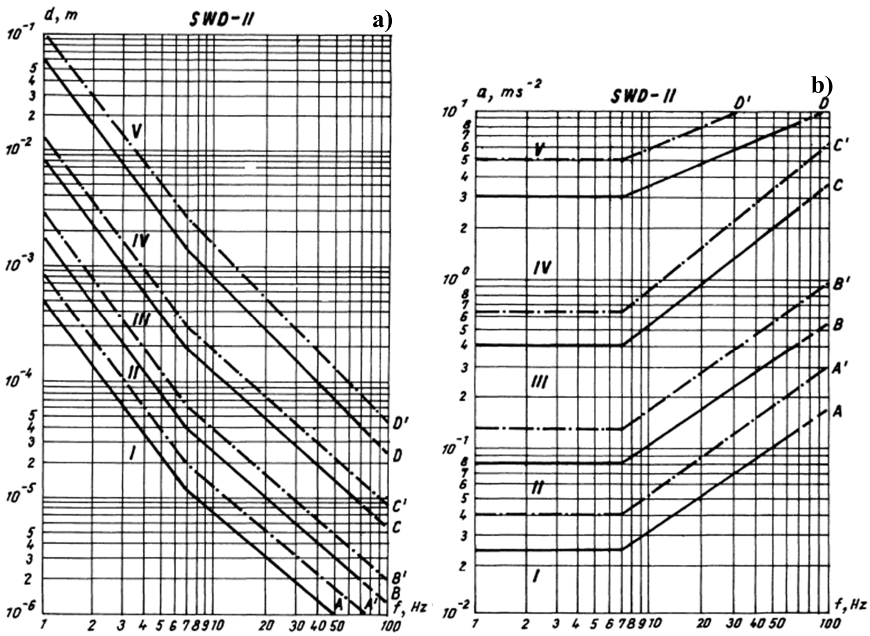


Fig. 2.10. Scale of dynamic influence on buildings DES-II (PN-85/B-02170 1985)

d) **technical measures that reduce the effects of dynamic actions on buildings**

Main technical measures that reduce the effects of dynamic actions on structures can be divided into the following three groups:

- with respect to the vibration source:
  – changes in technical parameters of vibration source,
  – offset of vibration source from the receiver,
  – active vibration insulation of vibration source;
- with respect to the vibration propagation path between the source and the building receiving vibrations:
  – the use of antivibration baffles in the substrate;
- with respect to the object receiving vibrations:
  – change of dynamic characteristics of buildings,
  – the use of passive vibration insulation of building or its elements,
  – moving buildings away from the vibration source*,
  – change in the method of foundation*.

The last two technical measures denoted with (*) may be considered in relation to existing buildings only in exceptional cases.

2.6.4. Assessment criteria of vibration influence on machinery and equipment installed in buildings

When determining allowable forced vibration amplitudes of foundations for machinery, the requirements of the supplier or manufacturer are at first taken into account. In the absence of strict requirements, the assessment of vibration influence on machinery is done depending on the sensitivity class of the machine to vibrations on the basis of Tab. 2.5. The specified criteria of the assessment are included in two groups: one related to machines and mechanical devices and the other related to precision devices. The magnitude, based on which the vibration influence on machines is assessed, is the permissible value of the effective velocity of vibrations (v_{per}). Five classes of sensitivity, of which the fifth denotes machines completely insensitive to vibrations, are provided. These are machines, which are the source of vibrations.

Tab. 2.5. Indicative breakdown of machinery and equipment into vibration sensitivity classes (PN-85/B-02170 1985)

Sensitivity class	Characteristics of sensitivity to vibrations	Name of machine or device	Permissible maximum velocity of vibrations v_{per} [mm/s]
I	Very sensitive	device for static and dynamic balancing, checking and regulating optical instruments, measurement microscopes, interferometers and other precise optical instruments, precise machine tools, measurement-control permanent instruments with accuracy to a few μm, rectification measuring instruments, electronic digital machines	0.1
II	Average sensitive	thread grinding machines, gear wheels, bearings, drilling machines and automatic milling machines, lathes with tolerances up to several μm, precise machines and precise machine tools	1.0

Tab. 2.5. Indicative breakdown of machinery and equipment into vibration sensitivity classes (PN-85/B-02170 1985) – *continued*

Sensitivity class	Characteristics of sensitivity to vibrations	Name of machine or device	Permissible maximum velocity of vibrations v_{per} [mm/s]
III	Not very sensitive	ordinary lathes, milling machines, drilling machines, grinders, machine tools of ordinary accuracy, textile, weaving and typographical machines	3.0
IV	Almost insensitive	engines, slotting machines, sewing machines, machine tools for light metals and wood, industrial presses, saws	5.0
V	Completely insensitive	fans, crushers, mills, shakers, tables and vibrating screens, screens, hammers, etc.	12.0

The vibration and shock influence on precision equipment in laboratories (microscopes, precision scales, optical measuring instruments, etc.) is assessed according to Tab. 2.5 for class I (very sensitive). As regards these machines the value of vibrations in one direction is not crucial, but the resultant value of vibrations is: v_x, v_y and v_z in three mutually perpendicular directions: x, y and z, which should satisfy the following condition:

$$v = \sqrt{v_x^2 + v_y^2 + v_z^2} \le v_{per} = 0.1 \text{ mm/s.} \tag{2.23}$$

In case of machines with fixed periodic movement, allowable amplitudes of forced vibrations, ensuring their harmlessness for the machine are given in Tab. 2.6, taking into account Lipiński (1998):

- adverse ground conditions,
- sensitivity to vibration influence of people being in the vicinity of the machine,
- the state of the building structure, in which the machinery is to be located,
- the vibration influence on sensitive equipment in the vicinity,
- other factors (production processes, etc.).

Tab. 2.6. Maximum permisible vibration amplitudes of foundations for machinery with fixed periodic movement (Lipiński 1998)

Direction of vibrations	Permissible amplitudes of forced vibrations A_{per} [mm], at the frequency of induced vibrations f [Hz]							
	0÷8	8	12.5	16	25	50	80	160
Vertical	150	120	90	75	60	30	15	5
Horizontal	200	160	130	110	90	50	20	7.5

For selected types of machines, maximum permissible amplitudes of vibrations are given in Tab. 2.7.

Tab 2.7. Maximum permissible amplitudes of forced vibrations for selected types of machines (Lipiński 1998)

Type of machine	Permissible vibration amplitude A_{per} [μm]
Turbogenerators ≥ 1000 MW	20
Turbogenerators <1000 MW	30
Weaving machinery	300
Spinning machines	100÷120
Machine tools, with the exception of precision machine tools	30
Rotary and jaw crushers	300
Piston machines	250÷300
Crank and screw presses, etc.	250
Hammers depending on the type of foundation	150÷1200

2.6.5. Assessment criteria for vibrations influence on humans in buildings

a) types and characteristics of vibrations affecting humans

Mechanical vibrations affect the human body. Effect of mechanical vibrations on human body is defined as human vibration. There are two main types of vibrations acting on the human body, i.e.:

- vibrations acting on the entire body,
- vibrations affecting mainly hands and arms when using tools.

The first of the above mentioned is the overall influence of vibrations. They are transferred to the human body as a whole, usually by a supporting surface, i.e. feet, buttocks, the back; e.g. a driver's body as a whole is exposed to vibrations transferred through the buttocks and possibly the back.

Operators using work tools are mainly exposed to the second type of vibrations. A human receives these vibrations through the contact of hand with vibrating tools. They are called vibrations with local influence. Both types of vibrations are "mechanically different" and are analysed separately. As a result, vibrations with the overall influence and vibrations with local influence on the human body at the workplace are assessed by different standards.

If a human, whose body is exposed to vibrations, does not support the vibration source and has no direct influence on this source, it is said that **it receives vibrations in a passive way**. Such situations occur when people being in residential rooms, offices, hospital rooms, etc., are mainly exposed to ceiling vibrations caused by different types of paraseismic actions. Most of the standards and guidelines in the literature discuss the influence of mechanical vibrations on people being in buildings and people receiving vibrations in a passive way. Several important pieces of legislation and recommendations – based on which harmfulness of vibrations on people can be assessed – are given in the following subsections.

b) assessment of vibration influence on humans based on standard PN-88/B-02171 (1988)

According to the provisions of standard PN-88/B-02171 (1988), sensitivity of the human body depends on many parameters. The human body is particularly sensitive to:

- direction of vibrations,
- vibration frequency,
- acceleration (velocity) of vibrations,
- time of occurrence of vibrations.

The standard PN-88/B-02171 (1988) introduced the following factors for the assessment of dynamic influences, which are characterised below:

- type of vibration excitation: continuous vibrations or shocks,
- direction of vibrations (reception): vertical, horizontal,
- purpose of building (e.g. housing, hospital, offices, workshops),
- time of occurrence of influence (day, night)

Breakdown by the type of vibration excitation:

In this breakdown, there are two main patterns of vibrations, i.e.:

– vibrations of sinusoidal type; change of the function course is a sinusoidal graph, ongoing for a very long time,

– vibrations of a single impulse (shock) in the source; representation taken at some distance from the source of then "vanishing" sinusoid,

– other types of vibrations such as: series of individual courses or vibrations of random type with variable parameters; in such cases the values with their amplitude-frequency spectrum or the maximum values are taken into account.

Breakdown by the direction of vibration reception:

Passive reception of vibrations by humans occurs in standing, sitting or lying positions. Vibrations can thus be carried by: feet, pelvis, back and head. Vibration measurements acting on humans are carried out in the orthogonal coordinate system whose focal point is the human's heart (Fig. 2.11.). The direction from head to feet is treated as longitudinal and is denoted with *z*. In this direction, the human's body is most sensitive to frequencies in the range of 4÷8 Hz. Human response at the level of vibrations in the *x* direction (forward – backward) and in the *y* direction (side – side) does not vary and is the highest in the frequency range of 1÷2 Hz. The coordinate system is permanently connected with the human body. This means that, for example, the axis for a person lying down will be the horizontal axis (Fig. 2.11.).

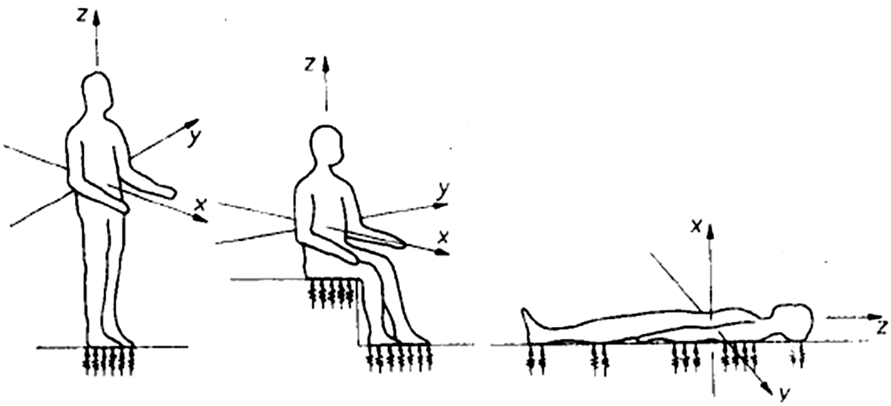


Fig. 2.11. The coordinate system and the human body positions illustrating the vibration nuisance on humans (Ciesielski et al. 1998)

Breakdown by functional purpose of buildings:

According to this breakdown, four categories of buildings are denoted:

– hospitals and buildings with special requirements regarding silence,
– residential buildings,
– offices and public buildings,
– industrial sites.

These criteria are also assigned to buildings with other functional purposes based on the logical assessment of similarity. In the building itself, several categories can also be distinguished, depending on the functional use of space.

Breakdown by the time of occurrence of dynamic influences:

When considering the time of day, in which vibrations occur, it was assumed that daytime is hours between 6 am – 10 pm, while night time is hours between 10 pm – 6 am.

As regards the transfer of vibrations to the whole human body, standard PN-88/B-02171 (1988) is limited to the consideration of vibration influence on humans with the frequency range of 1÷80 Hz. According to standard PN-88/B-02171 (1988), the assessment of vibrations influence on humans is conducted based on the measurement:

– adjusted in the frequency range of effective value of vibration acceleration,
– effective value RMS of vibration acceleration in 1/3 octave bands in the range of 1÷80 Hz.

c) the assessment of vibration influence on humans based on standard DIN 4150, part 2 (1999)

The German standard DIN 4150, part 2 (1999) gives the permissible values of vibration velocity for shocks (Tab. 2.8.), which are used for indicative assessment of vibrations influence for different areas of buildings. They concern the most adverse vibration direction (vertical or horizontal).

Tab. 2.8. Assessment of vibrations influence on humans in residential buildings and other (DIN 4150, part 2 1999)

Terrain characteristics	Time of day	Permissible vibration velocity [mm/s] for shocks	
		Continuous and repetitive with short breaks, but ongoing for more than two hours	Sporadic (up to three shocks per day)
Residential building	Day	0.2	4.0
	Night	0.15	0.15
Habitats buildings, mixed complex	Day	0.3	8.0
	Night	0.2	0.2
Service-related and office development	Day	0.4	12.0
	Night	0.3	0.3
Industrial zone	Day	0.6	12.0
	Night	0.4	0.4

d) assessment of vibrations influence on humans based on literature

In addition to guidelines, a few methods of assessment of vibrations harmfulness transferred to humans are given in literature. They mostly consist of either a descriptive definition of vibrations appreciability by humans or an indication of limiting values of selected parameters of vibrations (usually vibrations velocity).

Below are the two most known methods of assessment of vibrations influence on humans. The method of vibrations appreciability by humans was given by Ciesielski (1973), who described nine degrees of appreciability, depending on the frequency and displacement amplitude, velocity or vibration acceleration. Based on Ciesielski (1973), Fig. 2.12 shows a graph illustrating the relationship between the degree of vibrations appreciability and the frequency and amplitude of vibration displacement. The various degrees of vibrations appreciability are denoted as follows:

I – undetectable,
II – barely detectable when quiet,
III – detectable,
IV – clearly detectable,
V – strongly detectable,
VI – very strongly detectable,
VII – very strongly detectable and disturbing,
VIII – hard to bear,
IX – intolerable.

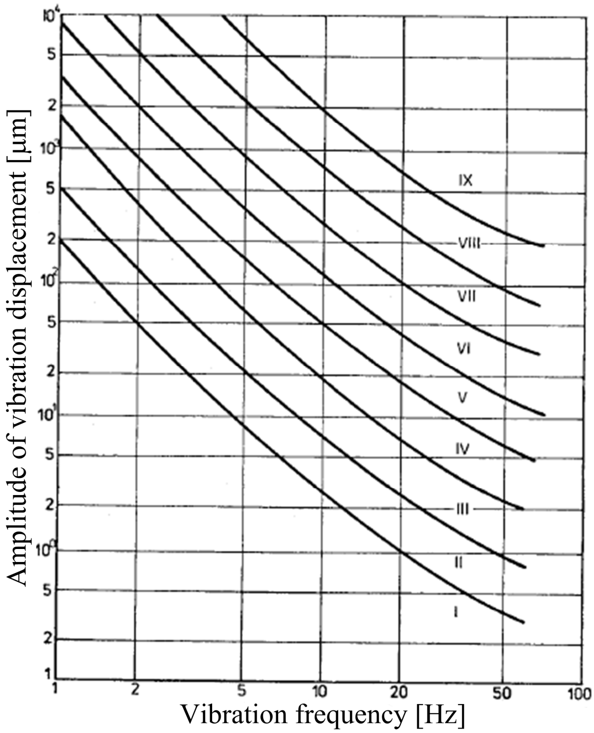


Fig. 2.12. Degrees of vibrations appreciability by humans (Ciesielski 1973)

In another source (Gutowski 1978), vibrations harmfulness is assessed based on the values of vibrations velocity that can affect humans, taking into account the building's purpose and time of day. Hourly range of times of day is specified in subparagraph b. The recommendations cited by Gutowski (1978) give the velocity amplitudes of transverse vibrations (horizontal) in buildings (Tab. 2.9), which can be considered as not bothersome. If the values given in Tab. 2.9 are exceeded twice, the vibrations will be felt by residents as moderately bothersome. Four times magnified, the vibrations will be felt as very bothersome.

Tab. 2.9. Acceptable vibration velocity amplitudes of buildings in transverse direction (Gutowski 1978)

Purpose of the building	The peak value of the vibration velocity [mm/s]
Hospital rooms	0.4
Residential buildings at night	0.5
Residential buildings in day	0.8
Offices	1.5
Industrial buildings	3.0

3. Types and specificity of work of RC structures loaded dynamically

3.1. Repository of RC structures loaded dynamically

Vibrations of buildings and other engineering structures are an integral part of their usage. Modern building structures can be subjected to considerable dynamic loads, which may have an impact on the usage and security of the building itself as well as the comfort of occupants. The type of forces depends on the purpose of the building, the place of its location and external conditions occurring in its environment. During the design process of RC structures, attention should be paid to dynamic effects caused by wind, earthquakes, machine operation, road and rail traffic, explosions in quarries, sea waves, etc. From this it can be concluded that dynamic loads can occur in all types of construction, e.g. building, industrial and road.

As indicated in Fig. 2.8, dynamic loads of deterministic or random character have an impact on RC structures. The group of structures, in which deterministic forces occur, includes mainly: **crane beams** and **foundations for machines**. The loads acting on crane beams are associated with the operation of the crane itself and the hoist or hoisting winch during lifting and transporting cargo. In the case of foundations for machines, dynamic load is caused by the operation of machines (which are based on those foundations). The problems associated with the determination of loads and with the design of both types of structures will be discussed in the following sections of the book.

A large group includes structures, in which exciting forces of random nature occur; the most common load is the wind effect. Tab. 3.1 summarises the majority of RC structures, which can be loaded dynamically in a random manner. For each structure, the type of occurring loads is also given.

It should be noted that Tab. 3.1 does not specify structures that could be subjected to random earthquake actions. These loads are not assigned to a specific type of structure as the sudden movement of the Earth's crust may act on all types of structures located in the seismic zone. It is worth mentioning that loads of this type are the most serious threat to tall structures such as skyscrapers and chimneys.

Tab. 3.1. Breakdown of RC structures loaded dynamically with random, exciting forces

<table>
<tr><td colspan="2">RC structures subjected to random forces</td></tr>
<tr><td>Type of structure</td><td>Type of load</td></tr>
<tr><td>Viaducts and bridges</td><td>Car traffic</td></tr>
<tr><td>Footbridges</td><td>Movement of people</td></tr>
<tr><td>Stadium grandstands</td><td>Movement and jumps of people</td></tr>
<tr><td>Cooling towers</td><td>Operation of fans due to wind impact</td></tr>
<tr><td>Fan coolers</td><td rowspan="5">Wind impact</td></tr>
<tr><td>Observation towers</td></tr>
<tr><td>Tall buildings</td></tr>
<tr><td>Chimneys</td></tr>
<tr><td>Suspension bridges</td></tr>
<tr><td>Onshore buildings</td><td>Wind effect, moving sea waves</td></tr>
<tr><td>Hydrotechnical structures, i.e.: dams, weirs, sluices, fish ladders</td><td>Water movement</td></tr>
</table>

3.2. Major problems concerning the design, construction and work of RC structures loaded dynamically

3.2.1. Specificity of RC structures loaded dynamically. Negative effects of dynamic actions

RC buildings designed to withstand dynamic loads and damping of vibrations are a specific type of structures that require a special approach from engineers during design, dimensioning and construction. Such structures should also be subjected to more detailed and more frequent inspections of durability in comparison to RC structures loaded only statically.

A meticulous approach in relation to design, construction and protection of RC structures loaded dynamically results from the two basic reasons described below.

The major factor is the presence of harmful vibrations in such structures, which in a short period of time may quickly lead to destruction of concrete as a result of the lack of complete monolithicity during construction (see Ch. 3.2.2.). The occurrence of primary surface discontinuities on external surfaces of RC solids subjected to impact of vibrations makes the resulting cracks gradually develop in depth, connecting or intersecting with each other. Over time, propagation of internal cracks can lead to more serious damage of structures such as spalling of concrete cover, crumbling of concrete pieces or breaking concrete into several separate pieces. In extreme cases, this can result in an emergency situation in structures.

The second important aspect that determined the uniqueness of approach to RC structures loaded dynamically is the occurrence of resonance in this type of objects (see Ch. 2.6.2.). The phenomenon of resonant vibrations is not very common and therefore designers can sometimes neglect this influence in calculations.

It should be remembered that the most important principle and assurance of the resonance absence is designing superstructure so as to ensure that none of natural frequencies λ is equal or close to the frequency of forced vibrations ω (see formula 2.20). The counteraction of the **transition resonance** may instead be done in two ways:

- application of **high tuning**, which is a selection of superstructure so that all natural frequencies were higher than the frequency of forced vibrations, i.e. $\lambda > \omega$,
- application of **low tuning**, which is a selection of superstructure so that all natural frequencies were lower than the frequency of forced vibrations, i.e. $\lambda < \omega$.

It should be added that the best way to avoid resonant vibrations is to design a structure which in any circumstances of dynamic extortion will be characterised by the occurrence of high tuning. The cases of low tuning are permissible only when the frequency of extortions occurs so fast that during short-term compliances $\lambda = \omega$, it will not result in the development of resonance.

In addition, during dimensioning of RC structures loaded dynamically, it is vital to carefully adopt static schemes and not to apply too much simplification in the course of calculation. The cross-sections should be chosen to be always on the safe side.

3.2.2. Characteristics of materials for construction of RC structures loaded dynamically

Requirements for materials used in construction of RC structures loaded dynamically are slightly different than the requirements to be met by materials of structures loaded statically. There are four main requirements for such materials:

- adequate strength,
- high fatigue strength,
- homogeneity of material,
- resistance to chemical and atmospheric influences.

Below are the most important specific requirements and instructions on the application of concrete and reinforcing steel in RC structures loaded dynamically.

a) **concrete**

The minimum class of compressive strength of concrete required in the case of RC structures loaded dynamically is C 12/15. The exception are RC structures transferring impact loads from operating machines, i.e. foundations under hammers. In such cases, concrete class C 16/20 – for smaller machines, C 20/25 and C 25/30 – for larger machines should be used. Specific recommendations for concrete strength classes required for specific types of foundations for machines will be presented in Ch. 4.1.2.

When selecting concrete strength class, for dynamically loaded structures, it should be taken into account that the lower the modulus of longitudinal elasticity, (i.e. the lower the strength class), the greater the fatigue strength is. Concrete of lower strength exhibits greater resistance to vibrations, which to a lesser degree reduces its compressive strength. In addition, high-strength concrete is characterised by increased brittleness when compared to ordinary concrete. For these two reasons, when selecting concrete parameters for structures loaded dynamically, never the main criterion is the high strength of material. However, it is important to always satisfy the minimum requirements.

Obtaining concrete with uniform characteristics throughout its mass is often more important than the high strength, as it is largely unused in RC structures loaded dynamically and any subsequent damage to these structures is often a result of mistakes made during concrete mixing.

Therefore, despite the apparent ease of concreting of massive structures transferring vibrations such as foundation blocks, all possible measures to ensure high-quality concrete should always be applied. Concrete should be homogeneous, without surface imperfections indicating the presence of honeycombs or porous areas, shrinkage cracks, etc.

All discontinuities occurring in concrete structure may diminish the ability of a structure to damp vibrations. In addition, it should be remembered that if a structure, which in the future is to transfer dynamic loads, has some weak areas, i.e. seams caused by pauses in concreting, they will inevitably be the beginning of structure cracking.

Both laboratory and practical experiments prove that the destruction from vibrations originates in the already damaged areas prior to the application of load. Concentration of harmful stresses in weakened areas has the effect of decreasing both the material’s durability and its resistance to aggressive surrounding environment. Microcracks and cracks occurring in the concrete also promote the corrosion of reinforcement.

Given the above, it is required to construct RC structures loaded dynamically from one batch – concreting from the beginning to the end without pauses.

b) **reinforcing steel**

Reinforcement of RC structures loaded dynamically aims not only to transfer tensile stresses and moments caused by external loads, but also its task is to protect concrete against formation of shrinkage cracks. These cracks, harmless in structures loaded statically, in elements working under dynamic loads may increase at a rapid pace (see Ch. 3.2.1), changing the rigidity and inertia of the system: structure – source of vibration.

Therefore, in structures loaded dynamically, the main reinforcement (transferring tensile stresses) from less brittle steel, i.e. lower classes, is preferred. It is sufficient to use reinforcing steel of regular C class, grade RB 300. It is permissible, of course, to use more brittle steel with higher yield strengths, i.e. RB 400 and RB 500. In such cases, however, an absolute verification of the serviceability limit state due to cracking is required - using only the exact method. Additionally, in order to avoid the occurrence of shrinkage cracks, a large amount of structural reinforcement, in which minor stresses form, is generally used.

The minimum amount of reinforcement in RC structures loaded dynamically is determined according to the recommendations given for specific types of structures (e.g. foundations for machines). In the absence of specific guidelines, general formulas given in PN-EN 1992-1-1 (2004) can be used.

3.2.3. Work of concrete and steel in the case of dynamic loads – fatigue of materials

Effects of material fatigue, caused by dynamic load resulting in the occurrence of variable stresses, manifest themselves in the possibility of destruction of the loaded element at stresses lower than those needed for the destruction of the same element, but loaded statically.

In the case of dynamic loads, material strength taken in the calculations depends on the number of cycles of stress changes, the value of the initial static stress, on which stresses will overlap and the ratio of minimum and maximum stresses. An additional factor affecting the strength is the presence of the so called notches, which may cause stress concentration.

The number of stress cycles N required to destruct the sample depends on the value of repetitive stresses σ. The number of load cycles applied during the use of buildings can reach up to 10^7, and occasionally even 10^8. The strength reduction *f* of material is not present when the number of stress cycles does not exceed 10^4. At the greater number of stress cycles *N*, strength decreases to the number of cycles N_G. After reaching the number N_G, the strength of sample f_G is already constant at any number of stress cycles. This value is called **fatigue strength** or **fatigue limit**.

In RC structures, the effects of dynamic loads and the process of material fatigue are analysed separately for concrete and separately for reinforcement. The detailed designs from which fatigue strength of both materials is determined will be given in Ch. 3.2.4. Below, however, are the major problems concerning this issue.

a) **concrete strength under fatigue load**

Constant vibrations, acting on RC structures, adversely affect concrete strength. According to Jamroży (2008), concrete subjected to apparent vibrations has its compressive strength reduced by about 40%, and dynamically loaded for a longer period of time – by up to 60%. The example of the stress-strain relationship ($\sigma - \varepsilon$) under cyclic compressive loading is shown in Fig. 3.1.

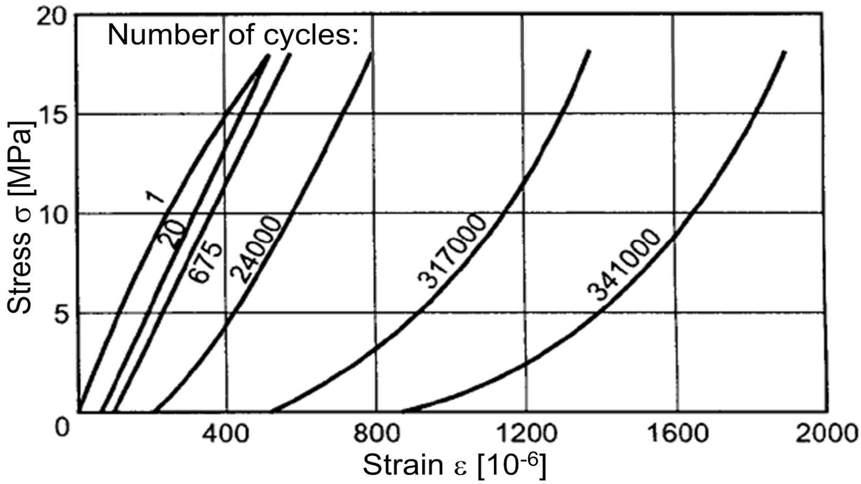


Fig. 3.1. Stress-strain relationship of concrete under cyclic compressive strength (Neville 2011)

In the case of concrete, curve $\sigma - \varepsilon$ changes with the number of load repetitions. During the progressive, cyclic load process, the transition of the curve $\sigma - \varepsilon$ through the following stages is distinguished (Fig. 3.1.):

- convex curve in relation to strain axis (with the hysteresis loop at unloading),
- straight line that shifts with decreasing velocity (some permanent strain is created),
- convex curve in relation to the stress axis.

During the last of the above stages, magnitude of convexity allows to conclude how close the destruction of concrete is. It should be emphasised that the destruction will occur only when the upper pulsation stress exceeds a certain limit value, which is called the fatigue limit. If this stress is lower than this limit value, curve $\sigma - \varepsilon$ will remain a straight line and fatigue failure will not occur (Neville 2011). A conventional fatigue limit as a fatigue strength for a large number of cycles, i.e. $2 \cdot 10^6$ is conventionally accepted.

Based on previous experimental studies and theoretical analyses, it was found that the fatigue of compressed concrete depends on the following factors:

- level and amplitude of loads,
- time and frequency of loads,
- history of load,
- concrete strength and its composition,
- structure of Interfacial Transition Zone (ITZ) between grains of coarse aggregate and paste,
- external environmental conditions, i.e. temperature and humidity.

It is assumed that fatigue of concrete is directly related to the emergence and enlargement of microcracks inside the cross-section of concrete. Development of microcracks during loading is an irreversible process corresponding to the damaged structure inside the material, evolving in the direction of failure.

As a result of the prevalence of fatigue loads, initiation of fracture processes in concretes most commonly occurs in ITZ between grains of coarse aggregate and paste. This is confirmed by analytical results obtained in experimental studies and during modeling of development of damages in concrete elements (Sadowski, Golewski 2008). In the case of two-dimensional analysis in the ITZ areas of coarse aggregate, the following microcracks are distinguished: straight crack and wing crack (Sadowski, Golewski 2008; Golewski 2015). The growth rate of this type of microcracks, their propagation and five other factors described above take place in several stages and depends mainly on the ITZ structure. A detailed description of particular stages of development of cracks in the ITZ aggregate – paste is shown later in Ch. 3.2.2.

A model based on the theory of critical stresses is most often used to estimate fatigue strength of concrete. This is related to fact that the growth and development of particular types of microcracks, i.e. straight and wing cracks, is closely related to the so-called **critical stress levels**. According to Hoła (2000), they are considered as meters of the state of concrete structure globally describing the process of its failure. Critical stress levels σ_{22}^{I} and σ_{22}^{II} are correlated with the moments of straight and wing crack initiations (Sadowski, Golewski 2008; Golewski 2015).

Figures 3.2. and 3.3. illustrate successive stages in development of cracks, appearing of representative grain aggregate with increasing load in ITZ, and Fig. 3.4 shows characteristic critical stress levels with description of particular stages, which involve development of cracks.

Figure 3.2. a shows a single inclusion with dimension of the side l_1, when stresses in the material are equal to zero or are significantly smaller than the first critical stress level, i.e. $\sigma_{22} < \sigma_{22}^{I}$. Fig. 3.2.a shows a reference coordinate system.

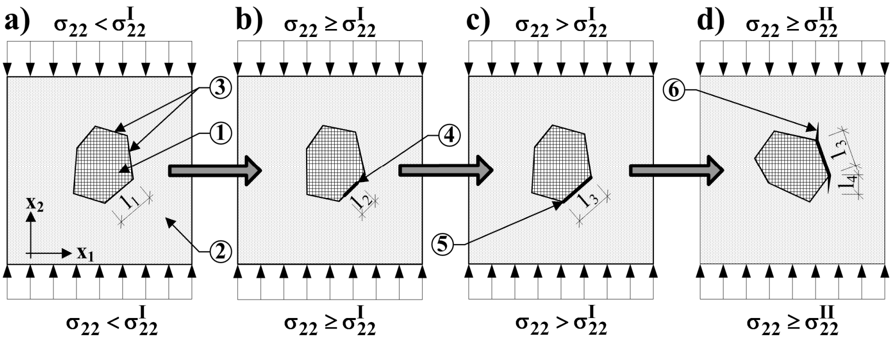


Fig. 3.2. Process of crack development of aggregate grain in ITZ: 1 – aggregate, 2 – matrix, 3 – ITZ, 4 – microcrack, 5 – mezocrack, 6 – wing crack (Golewski 2015)

In the first phase of element loading, microcracks occurring in the ITZ coarse aggregate remain in a stable state. At that time, the number of microcracks occurring prior to a load almost does not change, but their length and width of the opening slightly increases. This process continues up to the first critical stress level in the cross-section of the structural element i.e. when $\sigma_{22} = \sigma_{22}^{I}$. After stresses have exceeded σ_{22}^{I}, intensive, but stable development of microcracks occurs (Hoła 2000). Lengths and widths of straight cracks increase. Their number also increases steadily.

As a result of experimental studies, confirmed by subsequent computer simulations (Zaitsev, Wittmann 1981), it was found that the process of crack development (at fatigue loads) is a multistage phenomenon, linked directly with values of applied loads. Figures from 3.2.b to 3.2.d show the damage development on the grain boundary due to increasing external load. The process includes the following stages:

- at load larger than the first critical stress level, i.e. when $\sigma_{22} \geq \sigma_{22}^{I}$, initiation of straight microcrack with a length of l_2 occurs. Length of microcrack is considerably smaller than the grain size and the character of damage is only local (Fig 3.2.b),
- development of microcracks into the mezocrack with length l_3 occurring over the entire length of the grain (Fig. 3.2.c),
- unitial mezocrack growth in the secondary crack while changing the propagation direction as a result of encountering the energy barrier. At this stage of damage development, at load exceeding the second critical stress level, i.e. when $\sigma_{22} \geq \sigma_{22}^{II}$, wing crack with a small initial wing length l_4 (Fig. 3.2.d) is formed.

Further process of wing crack development depends on: type of stresses causing damage propagation (cracking model), level of the acting load, direction of wing propagation, mechanical-strength characteristics of individual phases of the composite. There are three cases of wing crack growth (Fig. 3.3.):

- wing propagation through matrix with length l_5 (Fig. 3.3.a), at stress level significantly exceeding the second critical stress level, i.e. $\sigma_{22} > \sigma_{22}^{II}$,
- wing propagation with length l_6 through matrix, up to a contact with other grain, and then the further crack growth with a length l_7 along ITZ of encountered inclusion (Fig. 3.3.b). In this case, the stress level in the damaged element is significantly larger than σ_{22}^{II}, i.e., $\sigma_{22} \gg \sigma_{22}^{II}$,
- wing propagation through matrix and coarse aggregate with length l_8 (Fig. 3.3.c). In this case, the stress level occurring in the damaged element is close to material strength, i.e. $\sigma_{22}^{III} \approx f_c$.

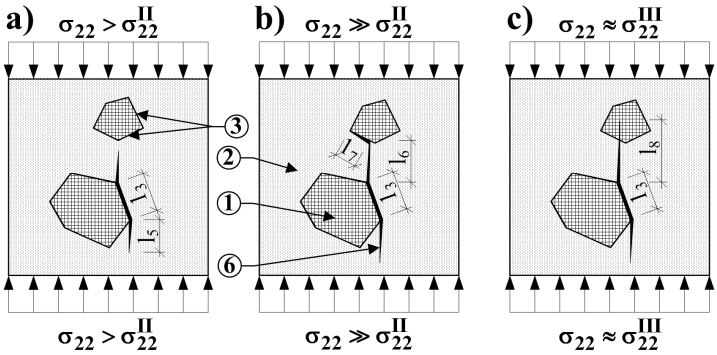


Fig. 3.3. Development of wing cracks: 1, 2, 3, 6 – as in Fig. 3.2. (Golewski 2015)

When external loads cause critical stresses σ_{22}^{II} in cross-sections of structural element, a sharp increase of the length of straight cracks and successive development of wing cracks occurs. This process leads to the formation of chains of cracks.

In the final phase of element loading, shortly before the material destruction, cracks pass through ITZ, matrix and grain aggregate. The cumulative length of cracks is then very large, which is confirmed by research carried with neutron radiography (Najjar, Hover 1989). As a result of experiments evaluating the development of internal cracks in cylindrical samples subjected to different types of compressive loads (including fatigue), it was established that there is a clear correlation between values of stresses and total length of microcracks (Najjar, Hover 1989).

At the stage of loading the concrete element, when $\sigma_{22} \geq \sigma_{22}^{II}$, propagations of straight and wing cracks become a dynamic process leading to the complete disintegration of concrete structure, regardless of whether the load increases or remains constant. Shortly after the appearance of stresses σ_{22}^{II}, part of wing cracks develops in an uncontrolled manner, which causes that the moment of destruction of material is only a matter of time of acting load.

The above-mentioned values of critical stress levels σ_{22}^{I} and σ_{22}^{II} (Fig. 3.4.) depend on the type of concrete composite and a number of technological and exploitation factors. The first stress level generally equals from 30% to 50% of load limit and the second from 70% to 90%. Detailed summary of ranges σ_{22}^{I} and σ_{22}^{II} for plane concrete and various types of special concretes, i.e.: polymer impregnated concrete, fibre-reinforced concrete, self-compacting concrete, high-performance concrete is demonstrated in Gorzelańczyk, Hoła (2015).

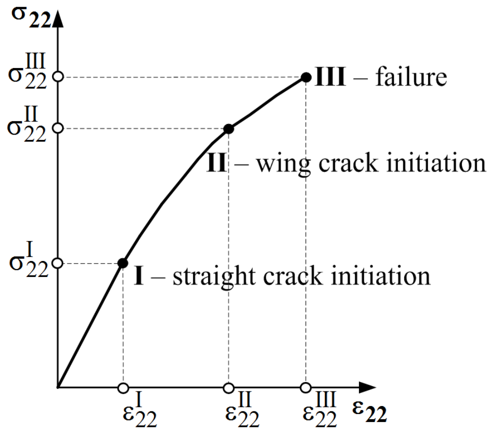


Fig. 3.4. Relationship of critical stress levels with the crack growth process

According to Santiago, Hilsdorf (1973) the largest increase in the length of microcracks and cracks, in the process of brittle fracture of material, occurs after exceeding the stresses equal to 0.85 a cube strength. For smaller loads have been observed slight crack growth (Santiago, Hilsdorf 1973). This level of stress thus corresponds to the stage of failures, where there are already wing cracks. Based on the analysis it can be concluded that the wing cracks plays a crucial role in the destruction of the concrete composites.

Figure 3.5. shows examples of wing cracks obtained after fracture toughness tests at Mode II fracture (Fig. 3.5.a) and at Mode III fracture (Fig. 3.5.b). In general, wing cracks consist of: a central straight crack (Fig 3.5. – 1) and two wings (Fig.3.5. – 2).

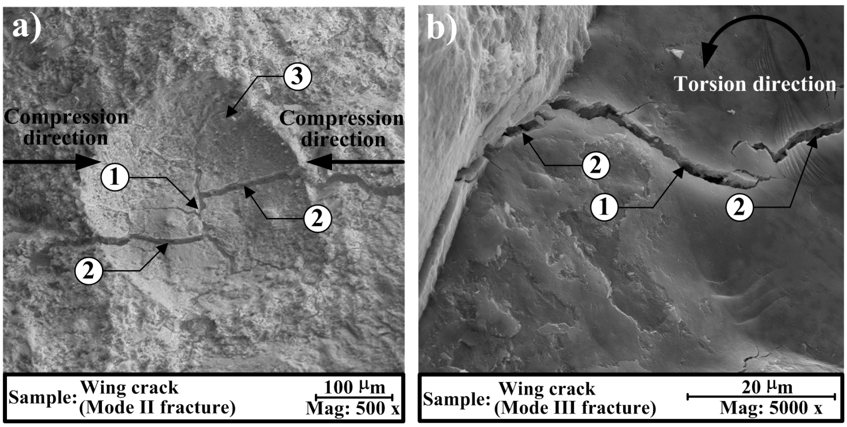


Fig. 3.5. Relationship of critical stress levels with the crack growth process; 1 – the central straight crack, 2 – wings, 3 – cavities in the place of separation grains from the matrix (photo by author)

Critical stress levels can be determined with the use of the method of direct and indirect measurement. The first group includes experiments evaluating σ_{22}^{I} and σ_{22}^{II} based on the observation of processes of formation and propagation of microcracks in concrete, e.g. X-ray microscopic methods. The disadvantage of these experiments is, however, a complex and expensive test equipment, and only a fragmentary analysis of stress destruction processes. In the broad range, methods for assessment of critical stress levels based on indirect measurements are common. These methods allow to monitor destruction processes specifying the phenomena occurring in a global manner. The most commonly applied experiments of this type include methods (Hoła 2000; Gorzelańczyk, Hoła 2015):

- the measurement of longitudinal and transverse unit deformations on the outer surface of samples as a function of compressive stresses,
- measurement of time of ultrasonic wave passage propagated in a direction perpendicular to the acting load,
- measurement of acoustic signals generated by material being damaged.

b) **steel strength under fatigue load**

The process of steel fatigue is cumulative and a fundamental material characteristic is the fatigue strength. It is usually expressed as the number of load cycles or in units of time. It is also used to determine the fatigue strength; it is expressed in unit of stress, typically in MPa. The course of fatigue variable loads typically has a stochastic character. The courses of repetitive magnitudes and frequencies of occurrence can also exist. These are periodically variable loads.

The simplest case of fatigue load of steel with a stochastic character is a variable sinusoidal load. It was adopted as the primary load – for a practical evaluation of fatigue properties of the material. In a series of sinusoidal variable stresses, there are distinguished (Fig. 3.6.):

- maximum and minimum stress cycle – σ_{max} and σ_{min} ,
- cycle asymmetry coefficient – R,
- cycle stress amplitude – σ_a ,
- mean cycle stress – σ_m ,
- stress change range – $\Delta\sigma$.

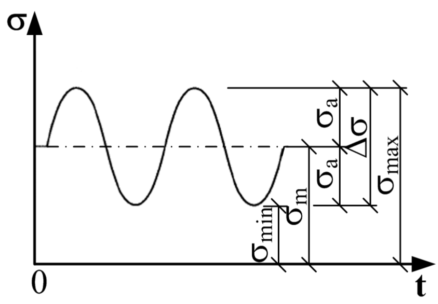


Fig. 3.6. Graph of variable stresses with stochastic character; denotations on figure are defined in text

Among the above parameters, relationships given by formulas 3.1÷3.4 are as follows:

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}, \tag{3.1}$$

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}, \tag{3.2}$$

$$\Delta\sigma = \sigma_{max} - \sigma_{min} = 2\sigma_a, \tag{3.3}$$

$$R = \frac{\sigma_{min}}{\sigma_{max}}. \tag{3.4}$$

The loss of strength of reinforcing steel, after a certain number of load cycles with specified parameters, is associated with changes in its structure. Fracture mechanics and steel destruction mechanics deal with these problems. They provide a solution to this issue at the level of elementary defect in the micro scale in the following manner. Application of multiple variable loads causes damage of structural bond network, thus reduction in strength of these bonds. The magnitudes of damages in steel microstructure depend on load values and the increase in the number of load cycles. According to Neimitz (1988), the velocity of fatigue crack development is characterised by *da/dN*, where *a* is the crack length, *N* – number of cycles, and can be represented as the following general formula:

$$\frac{da}{dN} = f\left(\sigma_a, a, C, Y, R, \eta\right), \tag{3.5}$$

where: σ_a, *R* – denotations as above, *a* – actual length of fatigue crack, *C* – material constants, *Y* – geometrical parameters of element or aperture, η – function representing load history.

Fatigue tests of reinforcing steel are carried out on bars in concreted and non-concreted states. More appropriate due to the adequacy of the model is the first one. They allow recognition of the impact such as: bar deflection, transverse force and concrete cracking, which in the case of non-concreted bars is impossible.

Most of fatigue tests of concreted simple reinforcing bars are carried out on concrete beams reinforced individually with transverse reinforcement. This provides a way to reflect the actual conditions of work of reinforcement in concrete elements subjected to bending, which in general case are subjected to combined action of bending moment – *M* and transverse force – *V*. As a result of combined effect of *M* and *V*, not only stresses in the direction of the bar axis occur, but also stresses perpendicular to them.

In the case of non-concreted bars, steel is subjected to two types of tests, i.e.:

- fatigue resistance by axial tension of the sample in the range of stresses varying sinusoidally at constant frequency,
- resistance to cyclic loads by subjecting steel sample to variable axial loads in the range of stresses, alternatively positive and negative.

Based on analysis of available in the literature test results, it can be concluded that, when calculating the fatigue strength of reinforcing steel, the following should be taken into account:

- number of load cycles,
- loading cycle parameters,
- bars deflection,
- bars diameter,
- type of surface of bars (smooth or ribbed),
- necessity for connection of bars,
- type and phase of work of concrete, in which bars are concreted.

As a result of conducted tests, it has been determined that due to fatigue strength – a better solution is to use smooth, not ribbed, reinforcing steel. Each type of ribbing of bars can be treated as an occurring notch, which is a potential stress concentrator.

The situation is similar in the case of connection of bars. First of all, it is advisable not to connect bars by welding. Connections of this type reduce the fatigue strength of reinforcing steel due to: stress concentration resulting from changes in the geometric shape of bars, formation of internal stresses from welding, changes in mechanical characteristics of steel in the immediate vicinity of the weld.

Diameter of reinforcing bars has a minimal effect on the fatigue strength of steel. Bar deflection has an adverse effect on the fatigue strength.

When considering the concrete quality, in which steel bars will be concreted, it can be seen that there was no clear differences in fatigue strength of the reinforcing steel (both smooth and ribbed bars), which was placed in ordinary and high performance concretes – with strength up to 600 MPa. It was also established that the effect of filler in concrete on the fatigue strength is negligible. Concrete adhesion and degree of compaction have a beneficial effect on the analysed parameter.

By analysing phases of work of RC element, it can be stated that in the element subjected to bending, working in phase I – non-cracked, participation of concrete in the transfer of tensile force causes a decrease in stresses in steel, which results in an increased number of load cycles required to achieve fatigue failure of the reinforcing bar. The formation of cracks causes stress concentration within them, creating stress notches. Scratching of concrete, therefore, reduces the fatigue strength of steel.

3.2.4. Physical characteristics of materials, important for design of RC structures loaded dynamically

When calculating RC structures loaded dynamically, coefficients of elasticity of materials and fatigue strength is needed to be known (see Ch. 3.2.3.). The important physical characteristics also include damping properties (energy absorption) of vibrations through the material and structure. Below are listed all important parameters, on which special attention is paid when designing RC structures loaded dynamically:

a) **modulus of elasticity of the material**

In dynamic calculations of RC structures, modulus of elasticity of concrete is primarily used to determine stiffness of structure. It should be determined experimentally, based on measurements of natural frequencies and amplitudes of forced vibrations of the model made of tested material. However, due to the fact that difference between static and dynamic stiffness of the structure is small (smaller than 6% for RC), values of modulus of elasticity, specified in standards, are obtained at static short-term load and can be used in dynamic calculations. The values of modulus of elasticity, for particular strength classes of concrete, are summarised on the basis of PN-EN 1992-1-1 (2004) in Tab. 3.2.

In practice, calculations of natural frequencies and amplitudes of forced vibrations – of typical RC structures – coefficients of elasticity are assumed as for concrete in compression, omitting the influence of reinforcement (values given in Tab. 3.2.). The exception are the so-called "responsible" structures, e.g. foundations under high-power turbine sets. In their case, it is necessary, prior to concreting, to check concrete strength of samples and determine its modulus of elasticity. The results of such studies should be close to standard values, which were adopted in static calculations.

Tab. 3.2. Modulus of elasticity of concrete used in calculations of dynamic structures according to PN-EN 1992-1-1 (2004)

Concrete strength class	Modulus of elasticity E [GPa]
C 12/15	27
C 16/20	29
C 20/25	30
C 25/30	31
C 30/37	32
C 35/45	34
C 40/50	35
C 45/55	36
C 50/60	37
C 55/67	38
C 60/75	39
C 70/85	41
C 80/95	42
C 90/105	44

b) **absorption of vibration energy and damping coefficient**

Building materials and structures made of them are characterised by the ability to absorb some of energy that causes deformations from stresses and dissipating it as heat energy. This ability is characterised by **energy absorption coefficient** – ψ , which is defined as the ratio of energy absorbed during one period of vibrations to energy corresponding to amplitude of deformation.

At the harmonically variable load, i.e. when $F = F_0 \sin \omega t$, absorption coefficient may be defined as the increased by 2π times value of the relationship of amplitude of inelastic deformation – y_r to amplitude of elastic deformation – y_s:

$$\psi = 2\pi \frac{y_r}{y_s}. \tag{3.6}$$

The value of absorption coefficient ψ depends on following factors:

- type and value of stresses,
- vibration frequency,
- ratio of dynamic to static stresses,
- temperature,
- age of structure.

The value of coefficient ψ for concrete and other selected construction materials are summarised in Tab. 3.3. while for building structures in Tab. 3.4.

Table 3.3. Values of energy absorption coefficient for certain construction materials (Lipiński 1998)

Type of material	Coefficient ψ
Pine and beech	0.01÷0.03
Brick wall	0.23
Concrete	0.26
Reinforced concrete	0.30
Steel profile	0.01÷0.03

Table 3.4. Values of energy absorption coefficient ψ for certain building structures (Lipiński 1998)

Type of structure	Coefficient ψ
Wood structures	0.30÷0.35
Brick masonry structures	0.25
RC structures	0.50
Steel structures	0.16÷0.18

An important observation, resulting from the analysis of both values ψ in the above table, is the observation of increase in energy absorption through structure (even by an order of magnitude) when compared to results obtained for materials of which these structures are made. The fact that values of coefficient ψ for building structures (Tab. 3.4.) are greater than for materials (Tab. 3.3.) results from the following three reasons:

- along with the basic material of structure, additional materials with improved energy absorption characteristics exist (e.g. steel structure with concrete or wall),
- energy absorption is increased due to use of different types of connections; especially in steel and wood structures,
- structures work spatially, so that the vibrations of one element are partially damped by adjacent elements.

In practice, non-elastic resistance coefficient called **damping coefficient** – γ is taken into account. It is determined using the following formula:

$$\gamma = \frac{\psi}{2\pi}\,. \tag{3.7}$$

The values of coefficient γ for different structures depending on dynamic category of machines generating vibrations (see Ch. 4.3.1.) is summarised in Tab. 3.5.

Table 3.5. Values of damping coefficient γ for structures made of different materials (Lipiński 1988)

Material of structure	Coefficient γ during the operation of machines	
	I and II dynamic category	III and IV dynamic category
Wood	0.030	0.050
Brick wall	0.040	0.080
Reinforced concrete	0.050	0.100
Steel	0.010	0.025

Based on the analysis of tables 3.3., 3.4. and 3.5, it can be definitely stated that the highest values of coefficients ψ and γ are for reinforced concrete and reinforced concrete structures. The favourable indicators of damping parameters, in the case of this type of materials and structures, indicate the legitimacy and indeed the necessity to apply them – in situations involving dynamic loads.

c) **fatigue strength**

When dimensioning RC structures loaded dynamically, it is absolutely necessary to take into account fatigue strength, if:

- stresses in cross-sections of structure's elements change at least $5 \cdot 10^5$, during the entire "life" of structure,
- variable loads constitute at least 60% of total load of the structure.

According to standard PN-EN 1992-1-1 (2004), in the ultimate limit states, partial factor of fatigue loads – $\gamma_{P,fat}$ can be taken based on national guidelines. The value recommended by standard PN-EN 1992-1-1 (2004) is 1.0.

The design fatigue strength can be determined in a simplified manner with the following formula. Relationship 3.8 is used for both brittle (concrete, brick wall) and plastic materials (steel, wood).

$$f_{fat} = S_{fat} \rho f_0 , \tag{3.8}$$

where:

$$S_{fat} = \frac{1 + k_0}{1 + \alpha_0 \mu_0 k_0} , \tag{3.9}$$

ρ – coefficient depending on the type of material selected from Tab. 3.6., f_0 – design strength of material for static load, k_0 – coefficient of symmetry of stress cycles, determined from formula 3.10.

$$k_0 = \frac{S_{dyn}}{S_{st}} , \tag{3.10}$$

α_0 – coefficient characterising fatigue strength of the material adopted in accordance with Tab. 3.6., depending on the type of structure's material, μ_0 – coefficient of stress concentration adopted in accordance with Tab. 3.7., S_{st} – generalised characteristic static force (normal force, transverse force, moment) in the considered cross-section of structure, S_{dyn} – amplitude of generalised, design dynamic force in the same cross-section of the structure.

Table 3.6. Values of coefficients α_0 and ρ to determine design fatigue strength f_{fat} (Lipiński 1988)

Material of structure	Coefficient	
	α_0	ρ
Rolled steel	3.0	2.0
Reinforced concrete:		
reinforcement	3.5	1.7
concrete	3.0	1.0
Brick wall	3.0	1.0
Wood	4.0	1.5

Table 3.7. Values of stress concentration coefficient (notch) for connections of structure elements (Lipiński 1988)

Connection type	Coefficient μ_0
Monolithic RC structures	1.0
Not weakened monolithic elements (between contacts and connectors)	1.0
Welded connection in steel structures:	
– butt welds (X, V, skewed)	1.4
– transverse fillet welds with the ratio of sides of weld's cross-section equal to 1:1.5:	
a) with weld dressing	1.7
b) without weld dressing	2.2
– longitudinal fillet welds:	
a) with weld dressing	2.3
b) without weld dressing	3.1
Riveted joints	1.4
Welded joints of RC prefabricated elements casted in-situ	2.3

4. Foundations for machines

4.1. Characteristics of foundations for machines

4.1.1. Role of foundations for machines

Foundations for machines are, in general, **special building structures** used to transfer loads from an operating machine to the subsoil.

Foundations for machines subjected to industrial dynamic loads are engineering structures that require a slightly different approach in design than structures transferring only static loads. The purpose of these foundations is not just to transfer loads, but also to **reduce vibrations occurring during operation of the machine, i.e. their damping and preventing redistribution to other elements of the building.**

A properly designed foundation for machine should satisfy a number of conditions, which are as follows:

- to provide appropriate support for the machine,
- to satisfy the requirements of the supplier of the machine for its installation and use,
- to have adequate strength, durability and stability,
- to reduce transfer of vibrations to surroundings to an acceptable level.

It should be noted that foundations for machines (particularly foundations for hammers) are **the most dynamically loaded building structures**. They are subjected to dynamic loads, the magnitude of which varies in short intervals. For these reasons, they require precise static and dynamic calculations. The most important problem in the analysis of this type of structure is the correct explanation and description of the operation of the system: **machine – foundation – subsoil**.

The general rules of shaping and designing foundations for machines are described in several monographs, e.g. (Lipiński 1988; Bhatia 2011; Prakash, Puri 2011; Arya et al. 1979; Srinivasulu, Vaidyanathan 1976; Meyer 1988), chapters in monographs, e.g. (Kameswara Rao 2011) and publications, e.g. (Mehta 2013; Bhandari, Sengupta 2014; Prakash, Puri 2006). The following subsections of the book characterise basic types of industrial machines including dynamic loads generated by them. Then, the main rules relating to the design of all types of foundations for machines will be discussed. This chapter also discusses the issues relating to the application of vibration isolation in the foundations for machines as well as practical recommendations – related to the construction of building structure and their later maintenance.

Due to the extensive scope of this chapter, the book omits a detailed analysis of the problem of subsoil in foundations for machines. In order to get acquainted with this topic, the author of the textbook refers the reader to the standard PN-EN 1997-1 (2004). In a wide range, these issues are also discussed in numerous literature references, e.g. (Lipiński 1988; Bhatia 2011; Prakash, Puri 2011; Arya et al. 1979; Srinivasulu, Vaidyanathan 1976).

4.1.2. Requirements for concrete strength classes

The general requirements relating to the use of concretes in RC structures loaded dynamically are presented in Ch. 3.2.2. In foundations for machines, the required minimum concrete strength classes depend on the type of machine and its dynamic category. In the case of certain groups of machines, for example turbine sets and hammers, the choice of concrete strength class is influenced by the parameters of the machine itself, i.e. its power – in the case of turbine sets and energy of a single impact of the beater – in the case of hammers. The concrete strength classes used in foundations for machines are summarised in Tab. 4.1.

Table 4.1. Concrete strength classes used in foundations for machines in accordance with PN-EN 1992-1-1 (2004)

Type of machines	Concrete strength class	
	Block foundations	Framework foundations
Machines with crank mechanisms (diesel engines, etc., crushers, mills, sieve screens, presses etc.):		
I, II and III dynamic category	C 12/15	C 16/20
IV dynamic category	C 16/20	C 20/25
Electrical and rotating machines (pumps, centrifuges, fans, generator sets):		
I, II and III dynamic category	C 12/15	C 16/20
IV dynamic category	C 16/20	C 20/25
Turbine sets with power:		
up to 20 MW	C 16/20	C 20/25
20÷100 MW	–	C 20/25, C 25/30
> 100 MW	–	C 25/30
Rolling equipment, machine tool	C 12/15	C 16/20
Single energy impact hammer – U:		
$U < 120$ kJ	C 20/25	C 16/20
120 KJ $\leq U \leq$ 400 KJ	C 25/30	C 16/20
$U > 400$ kJ	C 25/30	C 20/25

4.1.3. Requirements for foundations for machines during their operation

In addition to guidelines for the proper concrete selection, there are other relevant requirements relating to the foundations for machines concerning their proper reaction when taking loads from operating machines.

In foundation design, a dynamic character of the operating machine should be assessed as there are different requirements and different methods of calculation and construction of foundations for machines e.g. with the action of the impact and non-impact hammer. Based on Lipiński (1988), below are summarised and characterised some, more important, requirements relating to the foundations for machines. These include:

a) limitation of vertical settlements of the foundation

This limitation is achieved by such a foundation design that its pressures on the ground are lower than the acceptable pressure, and by the adequate preparation of the ground. In the case of strongly settling soils such as clays and soft-plastic dusts or loose sands, it may be necessary to design foundations on piles or vibration isolation.

b) limiting the uneven settlement

This is achieved by such configuration of the foundation base, so that the resultant of all self-weights and dead loads of the foundation pass through its centre of gravity, and in some cases, by the equalisation of stiffness of the foundation ground.

c) limitation of the deflections of framework foundations

This primarily concerns the deflections caused by factors occurring during the operation of the machine, i.e. temperature changes and service loads. The limitation is achieved by stabilisation of the factors causing deformations and by an appropriate selection of stiffness of loaded structural elements of the foundation

d) limitation of vibrations of foundation

Depending on the character of dynamic loads, vibrations are limited by suitable design of the foundation, which results in lower amplitude of forced vibrations to the allowable values in terms of the machine, subsoil, operation of the machine, near and further surroundings.

4.2. Principles of design of foundations for machines

4.2.1. Problems with design of foundation for machines

Due to the specificity of work of foundations for machines, an attention should be paid to the following aspects. In particular cases, they may cause some difficulties in this type of structure. The most common problems in design of foundations for machines include (Lipiński 1988):

a) thermal influences

They are reflected in uneven, adversely affecting the machine, deformations of heated parts of foundations (particularly framework foundations) or the formation of additional forces acting on the foundation, when the body of the machine heats up significantly stronger than the foundation.

b) overturning forces acting on the foundation

These forces can be: belt tensioning of the driving motor standing on a separate foundation or belt tensioning in belt conveyors as well as action of starting torque or moments of a short circuit. These forces are counteracted by a corresponding expansion of the foundation base.

c) monolithicity of the foundation structure

It is obtained by the use of high-quality concrete, proper reinforcement of the structure and appropriate concreting technology (see Ch. 4.9.1.), particularly, by avoiding breaks in concreting. The monolithicity of the structure is essential to provide the foundation with the established dynamic and static-strength systems.

d) corrosion of foundation

It manifests itself in corrosion of anchor bolts and metal parts in the foundation as well as in corrosion of vibration isolation. The corrosion is prevented by carrying out appropriate maintenance works (see Ch. 4.9.2.).

The chemicals, including technical oils, have also destructive influence on corrosion. These influences are prevented by the use of appropriate protective coatings (see Ch. 4.9.2.).

e) influence of vibrations on the environment

This influence should be reduced by locating the machines generating very strong vibrations away from sensitive objects or by the application of appropriate technical measures (vibration isolation) shutting off the source of vibrations.

f) determination of dynamic loads

In the case of certain machines, the determination of exact values of dynamic loads transferred to the foundation causes significant difficulties. This is often due to lack of data regarding the moving masses or complex character of their movement as well as other factors. It is then necessary to apply analogies to other machines with known loads or the determination of loads based on measurements of vibrations of existing foundations with known technical parameters.

4.2.2. Information relevant in determining the loads of foundations for machines and their breakdown

When designing and calculating the foundations and supporting structures for machines, the following loads are distinguished:

a) dead loads:
- self-weight of the foundation, ceilings and decks based on the foundation,
- weight of ground on the edges of the foundation,
- weight of the machine with moving parts (rotors),
- weight of the support equipment, technological installations,

b) long-term variables**:**
- from thermal deformations of the machine,
- from the vacuum of the condenser,
- from the temperature changes of pipelines,
- from shrinkage of concrete,

c) short-term variables:
- from load tests (hydraulic tests),
- assembly loads,
- from cranes based on the foundation,

d) dynamic, depending on the machine type:
e) special:
- short circuit,
- loads at the machine's failure,
- seismic loads.

In order to properly adopt values of static and dynamic loads, it is required to know many parameters of the machine.

The following information is required to determine the static loads of the foundation:
- weight of particular parts of the machine,
- type of support of the machine on foundation,
- arrangement in plan and the surface area of support of particular elements of the machine.

On the other hand, to determine the dynamic loads of the foundation, the following information is needed:
- dynamic scheme of the machine,
- values of dynamic loads: extreme absolute values, character of the variability in time, type (forces or moments),
- locations of application of dynamic loads,
- manner of attaching the machine to the foundation (dimensions and spacing of anchor bolts, their assembly load),
- engine drive (engine, transmission belt),
- rotation frequency of the machine and drive.

4.3. Basic types of machine loads related to their operation

4.3.1. General classification of machines

For the design purposes of foundations for machine, it is basically needed to know loads generated during the operation of machine, which are transferred to the foundation, causing its movements. For this reason, the breakdown of machines is by the type, value and frequency of occurrence of generated by them dynamic loads.

Many types of machines generate dynamic loads so insignificant that they do not have significant impact on the foundation. For these machines, design of the foundation is virtually a static issue. Such machines are defined as **quiet machines**. The second group are the machines that generate significant dynamic loads, having a significant impact on the foundation. These are known as **unquiet machines**.

An exact breakdown on quiet and unquiet machines is often difficult to carry out. The assessment based on the observation of the machine during its operation is decisive. This particularly applies to machines with complex mechanical system.

In further considerations, unquiet machines are subjected to a thorough analysis. The following summarises the classification of these machines according to various criteria. With this knowledge, it is possible to characterise the machine to determine how to proceed with the design of the foundation or support structure and to what extent to conduct the calculations. The breakdown of machines according to different criteria is as follows (Lipiński 1988):

Breakdown by the dynamic influence on the foundation

a) machines with established and regular dynamic action:

- with uniform rotation, e.g. electrical machines (engines, generator sets, compensators, etc.), turbine sets (turbo generators, turbo pumps, turbo blowers, etc.), rotary compressors, fans, centrifuges, etc., some machine tools (lathes, grinders, drills, etc.), centrifugal pumps,
- with uniform rotation and coupled with it reciprocating motion, e.g. crank machines (piston steam engines, compressors and pumps), combustion engines, some of the machines, vibrating screens, mills, crushers, vibrating tables,

b) machines with unidentified and irregular dynamic action:

- with non-uniform rotation or non-uniform reciprocating motion, e.g. rolling equipment engines, short-circuit generators, vibration simulators, laboratory machines for research,
- with reciprocating motion, resulting in a single impact or series of impacts, loads with impulse character, e.g. free forging hammers, drop forging hammers, presses, some machine tools (slotting), scissors, machines for strength tests.

Breakdown by the type of motion:

a) reciprocating vertical,
b) reciprocating horizontal,
c) rotary about a vertical axis,
d) rotary about horizontal axis.

Breakdown by the rotational speed:

a) small – up to 500 rpm,
b) average – 500÷1500 rpm,
c) large – 1500÷5000 rpm,
d) very large – above 5000 rpm.

Breakdown by the magnitude of dynamic loads: dynamism category of machine:

a) low dynamism – up to 0.1 kN; I category,
b) average dynamism – 0.1÷1.0 kN; II category,
c) high dynamism – 1.0÷3.0 kN; III category,
d) with very high dynamism – more than 3.0 kN; IV category.

In the following subsections of Ch. 4.3, three groups of machines are characterised, i.e.: rotating machinery, piston machines and hammers. The selection of such groups of machines is based on the fact that each of them generates a very different type of dynamic loads while working, which must be taken into account in the calculations of foundations.

In the case of rotating machines, an attention should be paid to the presence of centrifugal force and sometimes the short circuit. In piston machines, the dominant are component forces of the cylinder, resulting from work of reduced masses of the crank mechanism. The hammers – as representatives of the machines with the greatest work dynamism – generate loads in the form of strong impulses.

Information about forces, generated by other types of characteristic noisy machines such as crushers, mills, vibrating tables and vibrating sieves can be found in Lipiński (1988).

4.3.2. Rotating machines

The basic types of rotating machines, i.e. machines with uniform or non-uniform rotation, are summarised in Ch. 4.3.1.

The main forces, which are generated by rotating machines, are **centrifugal forces**. They are generated during the work of rotating elements of the machine.

It should be noted, however, that such forces occur only, if the rotating parts of the machine are not formed in an ideal way. This results in the occurrence of the so-called cases of dynamic unbalance of machines, which include:

- **static unbalance** – when the geometrical axis of the rotor and its main central axis of inertia are parallel (Fig. 4.1.),
- **moment unbalance** – when the geometrical axis of the rotor and its main central axis of inertia are inclined.

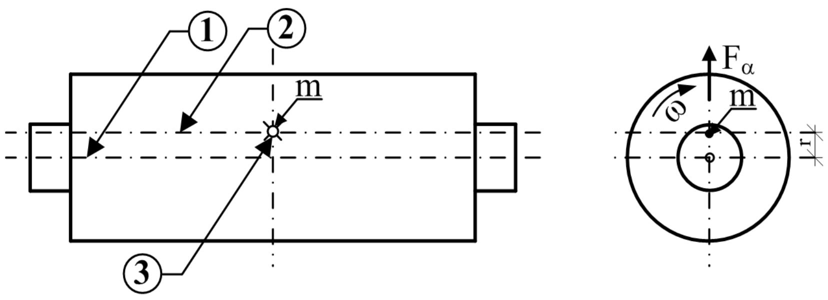


Fig. 4.1. The inertia forces resulting from static unbalance of the rotor; 1 – geometrical axis of the rotor (axis of rotations), 2 – main axis of inertia of the rotor, 3 – the centre of gravity of the rotor, *m*, *r*, *ω* – description in text

The centrifugal force adopted in the calculations of foundations for machines is determined on the basis of formula 4.1.

$$F_{\alpha} = mr\omega^{2}, \tag{4.1}$$

where: m – mass of rotating parts of the machine [kg], r – eccentric of rotating mass [m], $\omega = \frac{2\pi}{60} n_m = 0{,}1047 n_m$, n_m – angular velocity of rotations of the rotor [rad/s].

In electrical machines, in addition to centrifugal machines, there may be an additional dynamic load, which occurs as a result of a short circuit in a generator or motor. Then, **short circuit moment** occurs, which acts on the foundation as a couple – F (Fig. 4.2.) defined with the relationship 4.2.

$$F = \frac{M_z}{a}, \tag{4.2}$$

where: M_z – short circuit moment [kN·m], a – distance between rows of stator side mounting screws to the foundation [m].

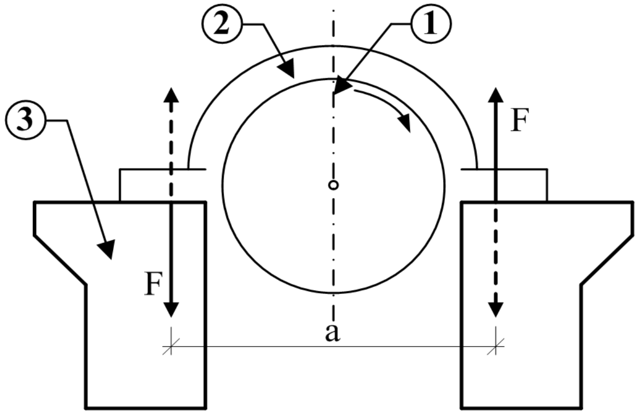


Fig. 4.2. Short circuit moment acting on the foundation; 1 – axis of the generator, 2 – generator, 3 – foundation.

4.3.3. Piston machines

In piston machines (crank) masses undergo a rotation movement and coupled with it reciprocating motion. The main types of machines of this type are summarised in Ch. 4.3.1.

The system of the crank mechanism is shown in Fig. 4.3. The excitation forces in crank mechanisms are forces of inertia of unbalanced masses of moving parts of mechanisms. The pressure in the cylinder is the internal force and does not act on the foundation.

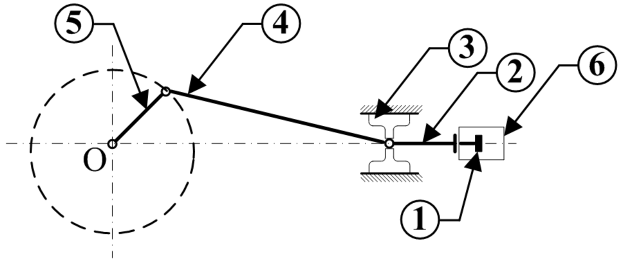


Fig. 4.3. Crank mechanism system; 1 – piston, 2 – piston rod, 3 – slider (bolt), 4 – connecting rod (connector), 5 – crank shaft, 6 – cylinder of the piston

The piston with the piston rod and slider performs a reciprocating motion. The crankshaft performs a uniform rotational motion about the main axis of the shaft O. The connecting rod performs a complex periodic motion. As a result of motions of all these elements of mechanism, forces of inertia that cause vibrations of the foundation are generated.

To calculate the forces of inertia generated in crank mechanisms, a simplified diagram of a moving mass is considered (Fig. 4.4.).

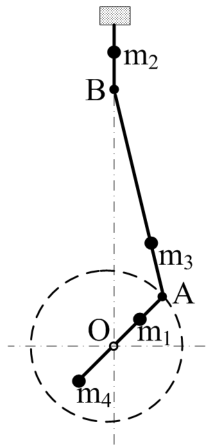


Figure 4.4. The system of basic masses of crank mechanism; $m_1 = m_1^{'} + m_1^{''}$ **– crank mass,** ***m₂*** **– mass of moving parts with reciprocating motion., i.e. piston rod, slider,** ***m₃*** **– connecting rod mass,** ***m₄*** **– counterweight mass**

Masses m_1, m_2, m_3 of three essential parts of the mechanism come down to two point loads in points: A – crankpin fillet and B – slider. Formulas to calculate reduced masses are given below.

$$m_A = \frac{r_1}{r} m_1^{'} + m_1^{''} + \left(1 - \frac{l_1}{l}\right) m_3 - \frac{r_o}{r} m_4 , \tag{4.3}$$

$$m_B = m_2 + \frac{l_1}{l} m_3 , \tag{4.4}$$

where: r – crank radius [m], r_1 – radius of the centre of gravity of the crank [m], r_o – radius of the centre of gravity of the counterweight [m], l – length of the connecting rod [m], l_1 – distance of the centre of gravity of the connecting rod from the axis of crankpin fillet [m], $m_1^{'}$ – crank arm, $m_1^{''}$ – crankpin fillet, m_2 – parts moving with reciprocating motion, m_3 – connecting rod, m_4 – counterweight.

The excitation forces generated in each cylinder can be decomposed into a component Q – acting in the direction of the movement of piston, and component F – acting in a direction perpendicular to the movement of the piston.

The most important when calculating the foundations for machines are the excitation forces of the first order with velocity of vibrations equal to the rotational velocity of the shaft of machine. These formulas are given below.

$$Q_i = r\omega^2 \left(m_{Ai} + m_{Bi}\right) \cos\left(\omega t + \beta_i\right), \tag{4.5}$$

$$F_i = r\omega^2 m_{Ai} \sin\left(\omega t + \beta_i\right), \tag{4.6}$$

where: Q_i, F_i, – component forces of the cylinder i, r – as in formula 4.3., ω – angular velocity of rotations of the shaft [rad/s], m_{Ai}, m_{Bi}, – reduced masses of the cylinder i, t – time [s], β_i – wedging angle of the crank of the cylinder and in relation to the crank of the first cylinder, for which β_i=0 [rad].

4.3.4. Hammers

Forging hammers belong to the group of equipment, which is characterised by high and even very high dynamism. The loads occurring during the operation of hammers are short impulses of considerable values generated by excitation forces.

The main types of forging hammers are **free forging hammers** and **matrix hammers**. Fig. 4.5 shows pictures (during the operation) of two examples of matrix hammers and a detailed breakdown of hammers along with the masses of their beaters are given in Lipiński (1988).

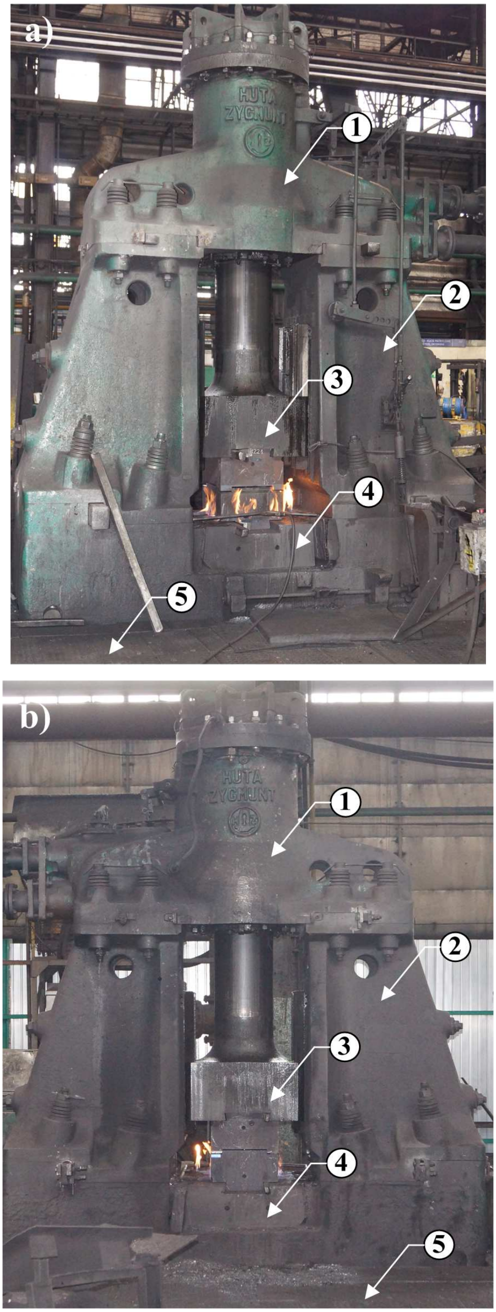


Fig. 4.5. View of two types of matrix hammers produced by Huta Zygmunt: a) MPM 600, b) MPM 1000 B; 1 – head hammer, 2 – body hammer, 3 – beater, 4 – hammer anvil, 5 – working platforms (photo by author)

The operation of the hammer, that is a **forging process,** is when the kinetic energy of the beater falling with a high speed onto the anvil and associated parts is processed into the work of deformation of the material heated to a plastic state, from which the forging is obtained. This process is accompanied by transfer of part of energy of impact on the hammer, which causes excitation of vibrations.

The vibrations caused by the impact are transferred to elements of foundations and propagate in the subsoil surrounding the foundation. The effects of the operating hammer are, therefore, felt not only in the immediate vicinity of the foundation. They may also cause interference within a radius of several hundred meters from the location of forging.

For these reasons, foundations for forging hammers are included in the building structures heavily loaded dynamically and require an individual approach. The following describes how determined are and on which depend dynamic loads that occur during the operation of hammers while detailed guidelines relating to the design of foundations for hammers will be presented in Ch. 4.7.

The loads that cause vibrations in hammers are impacts of the beater in the forging resting on the anvil (anvil head). The **beater impact** is of **impulse** character of value:

$$I = (1+k)\, m_0 v_0, \tag{4.7}$$

in which: m_0 – mass of the falling parts i.e. beater with the upper matrix [Mg], v_0 – velocity of the beater at the moment of impact [m/s] k – coefficient of impact.

The velocity of the beater of hammer at the time of impact depends on the type of hammer. For any type of hammer, the velocity is determined from the balance of energy of the impact of the beater – U and kinetic energy of mass of the beater with the upper matrix set in motion – m_0. Thus:

$$v_0 = \sqrt{\frac{2U}{m_0}}\,, \tag{4.8}$$

where: U – energy of the full impact [kJ], m_0 – as in formula 4.7.

Indicatively, velocity v_0 can be taken depending on the mass m_0 according to the following guidelines:

- if $m_0 < 1{,}0 Mg$ then v_0 = 8.0 m/s,
- if $1.0 Mg \le m_0 \le 3.0 Mg$ then v_0 = 7.0 m/s,
- if $3.0 Mg < m_0$ then v_0 = 6.5 m/s.

The value of coefficient of the impact k depends on a number of technological factors, among which the most important are:

- shape of the forged element,
- temperature of the forging material,
- size of the contact surface during the impact,
- weight of the upper matrix and beater.

The coefficient of the impact *k* defines the character of collision of two bodies; for value $k = 0$, the collision is perfectly plastic, while for $k = 1.0$ – the collision is perfectly elastic.

A proper selection of coefficient *k* is important when designing and, therefore, its value should be specified in design assumptions, depending on the intended purpose and method of operation of the hammer.

Table 4.2 and 4.3 present (Lipiński 1988) an indicative compilation of values of impact coefficients *k* that depend on the type of steel machining in hammers and intended purpose and method of operation of the hammer. However, it should be noted that information of sizes provided in tables certainly does not cover all possible cases. Therefore, in practice, with the absence of specific data, commonly accepted is $k = 0.5 \div 0.6$.

Table 4.2. The values of impact coefficient *k* depending on the type of treatment (Lipiński 1988)

Type of steel treatment	Coefficient *k*
Slight hot flattening	0.2
Initial hot flattening	0.3
Final hot flattening	0.4
Cold flattening	0.5
Initial impact during matrix forging	0.6
Finishing impacts during matrix forging	0.7
Matrix hard works	0.8

Table 4.3. Values of impact coefficient *k* depending on the type of hammer (Lipiński 1988)

Purpose and method of operation of the hammer	Coefficient *k*
Matrix hammers when forging steel	0.5
Matrix hammers when forging non-ferrous metals	0.4
Free forging hammers	0.25

4.4. Breakdown and structural systems of foundations for machines

4.4.1. Breakdown of foundations for machines depending on the machine type based on the foundation

Depending on the type of machine located on the foundation, there are distinguished:

a) foundations for machines with impact action

Machines in those foundations act on them during work with a single impulse or series of impulses. Such machines include, among others, mechanical hammers and pile drivers.

b) foundations for rotating machines

Dynamic impacts of machines in these foundations generate centrifugal forces of rotating parts. Such machines include: turbines, generators, fans, pumps.

c) foundations for machines with a crank system

The dynamic action of such machines is caused by the reciprocating motion of certain parts of the machine. Machines, which include: combustion engines, reciprocating machines, surface planing machines, most often cause harmonic variable forces.

d) foundations for machines of crusher type

The dynamic impact of such machines is caused by motions of breaking or crushing elements. Such machines include: breakers, crushing mill, stone crushers.

e) foundations for other machines

This group includes the foundations for machines such as rolling machines, machine tools for metal. The dynamic impact of such machines on the foundation can be different depending on the type of machine operation.

4.4.2. Main structural systems of foundations for machines

The structure of foundations for machines depends primarily on the dynamic character of work and dimensions of the machine.

If a quiet machine, performing slow or fast movements, is placed on the foundation, however, the mass of elements in motion is in relation to the total weight of the machine small, the foundation will have a simple structure and will be very similar to any other foundation for other building objects.

A more complex group are structural systems of foundations for unquiet machines. In order to systematise the methods of design and construction of engineering structures subjected to industrial dynamic loads, a conventional breakdown of foundations for such machines on three essential groups is introduced:

- I group – **block foundations**,
- II group – **framework foundations**,
- III group – **support structures**.

It should be noted, however, that there are structures that combine characteristics of different types of structures such as **box foundations**, **wall foundations** or platforms loaded with machines, similar to framework systems.

In addition, due to the specificity of hammer operation, which generates dynamic loads in the form of impulses, in the group of block foundations, there is a breakdown: **block foundations for non-impact machines** and **foundations for hammers**.

In the following chapters, detailed characteristic and main principles for shaping and design of foundations for quiet machines and all groups of foundations for unquiet machines are presented.

4.5. The simplest foundations for quiet machines

In foundations for quiet machines, length and width of the foundation depend only on the dimensions of the machine. The basis of such foundation is a slab with a thickness dependent on the screw length with the use of which the machine is to be attached to the foundation. The quiet machines most often are placed on RC slabs, however, it is also acceptable to apply solutions in the form of concrete slabs without additional reinforcement. To transfer small dynamic loads, slabs with a thickness from 30 to 40 cm are sufficient.

4.6. Block foundations for non-impact machines

4.6.1. Characteristics and types of block foundations

The block foundations are the most commonly used type of foundation for unquiet machines. They are used for the following types of machines: reciprocating; both steam and combustion engines, compressors, electric motors, fans, pumps, mills, matrix and free forging hammers.

The block foundations are in the form of a massive body, of more or less regular shape. In such solid, there may be notches, indentations and openings for cables, the location of auxiliary equipment and the machine (Fig. 4.6.). The block foundations are constructed in the form of full block or adequately thick slab.

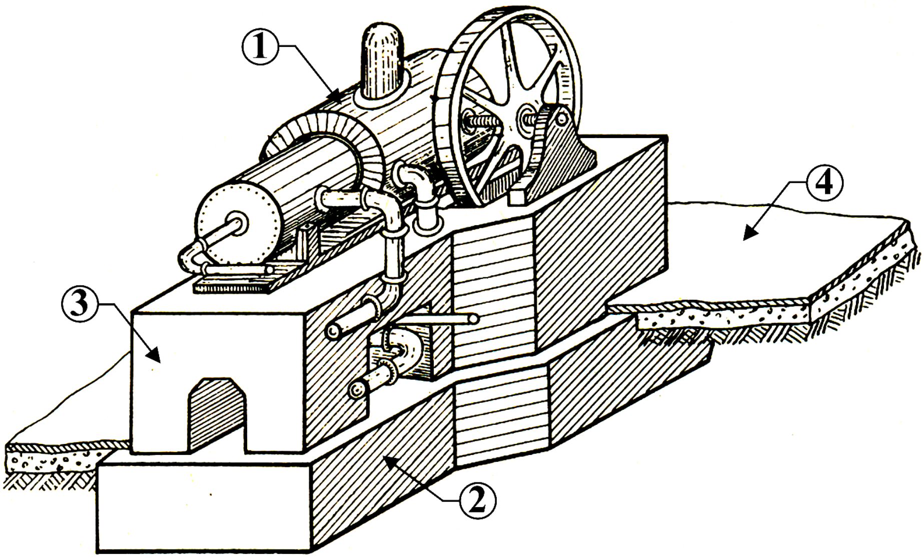


Fig. 4.6. Block foundation for machine (Kral 1973); 1 – the machine, 2 – bottom slab of the foundation, 3 – upper part of the foundation, 4 – the floor of the room

A certain variety of block foundations are the box foundations. They may have a form of an open box, as for example shown in Fig. 4.7., or closed, forming a monolithic closed box.

Depending on technological requirements, block foundations may have a high above-ground section, reaching even up to the level of the next floor of the building, or they may end up directly above the lowest floor level.

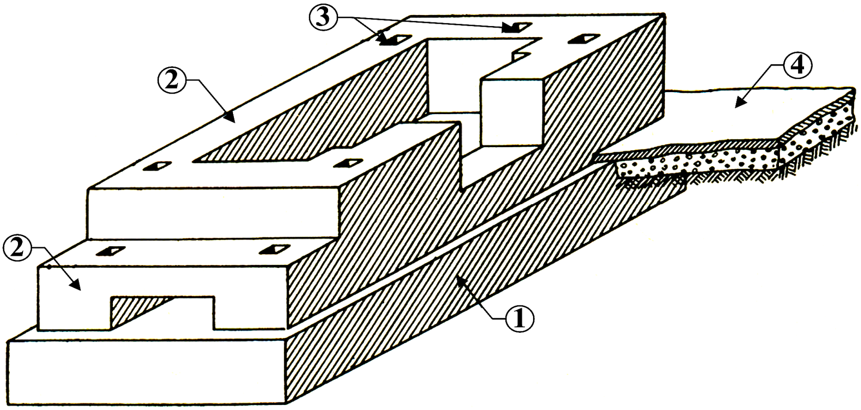


Fig. 4.7. Box foundation for machine (Kral 1973); 1 – bottom slab of the foundation, 2 – upper part of the box, 3 – anchor holes for fixing the machine, 4 – lower slab of the foundation

Generally, due to the structure and dimensions, i.e. width and height, among block foundations, there are distinguished (Fig. 4.8.):

a) foundation blocks

- low foundation blocks, if $\frac{H}{B} \leq 1$,
- high foundation blocks, if $\frac{H}{B} > 1$,

b) wall foundations (box)

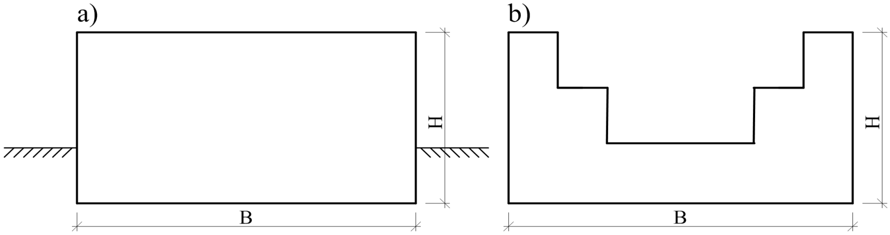


Fig. 4.8. Schemes of block foundations; a) foundation block, b) wall foundation

The essential characteristics of the block foundation is its considerable stiffness, which in dynamic calculations enables the omission of deformations of the structure itself and treatment of the foundation as a rigid body on the elastic substrate. The ability of the foundation to perform vibrations results in this case only from the elasticity of the ground or other substrate, on which it is constructed.

4.6.2. Information necessary in foundation design

In a design of block foundation, two groups of data are required, which include:

a) data characterising the machine:

- general characteristics of the machine – the nave, type, rotational speed, power, weight, etc.,
- data about the location of the machine on the foundation and the type of its attachment,
- drawings of the upper part of the foundation showing the technological installation and the use of the machine (including data about bearing plates, foundation bolts, grout, steel elements in concrete, etc.),
- data on auxiliary equipment or installation related to the machine,
- scheme of arrangement and size of all static loads of foundations,
- data needed to determine the size, direction and type of action of dynamic loads caused by the operation of the machine or the best – the size and nature of the action of dynamic loads,
- other requirements or technological and exploitation data.

b) data characterising conditions in location, where the machine is to be placed:

- information about the subsoil and water conditions of terrain with the results of tests of physical and mechanical characteristics of the soil, allowing its classification and assessment of ground in exploitation conditions of the object,
- locating the machine in the building giving the foundation depth and dimensions in the plan view of foundations of adjacent structures, both of the building and other objects,
- information about special requirements due to the presence of equipment or premises and possibly buildings sensitive to shocks and vibrations in the vicinity of the machine, with the identification of the distance of these objects from the machine and specification of the allowable for these objects vibration amplitudes.

4.6.3. General principles of block foundation design

The design of block foundations involves mostly proper selection of the geometry of a solid of the foundation. The following summarises the most important guidelines for the selection of the dimensions of block foundations and shaping their base.

a) geometry of the foundation and depth of its foundation

When designing the dimensions of the block foundation, the minimum height of the foundation block should be established in order to decrease the range of earthworks, and then to select dimensions of it in a horizontal plan to satisfy other requirements and dynamic conditions, in particular a condition of quiet work of the foundation.

When determining the minimum height of the foundation, an attention should be paid to three requirements, which are schematically shown in Fig. 4.9.÷4.11. They concern:

- **minimum foundation depth**

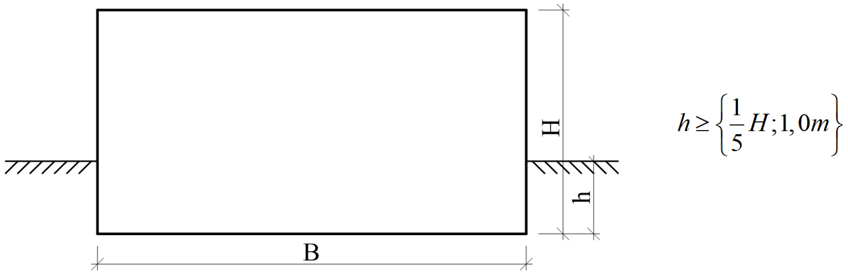


Fig. 4.9. Conditions for the selection of minimum depth of the block foundation

- **depth of anchor bolts in the foundation**

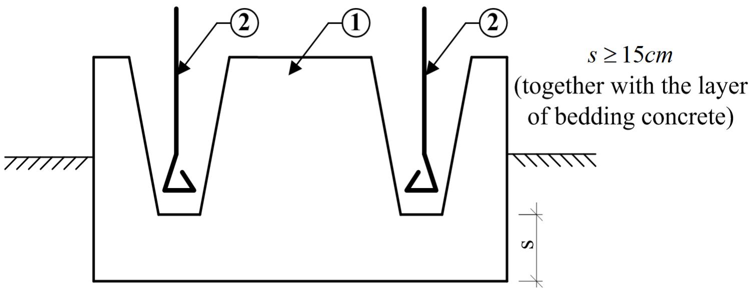


Fig. 4.10. The condition relating to the protection of holes for anchor bolts; 1 – the foundation, 2 – the anchor bolt

- **level of cavities occurring in the foundation**

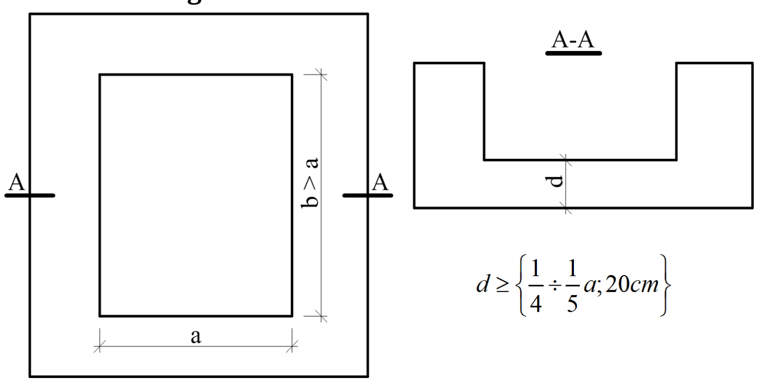


Fig. 4.11. Conditions for the selection of a minimum thickness of concrete in the zones of cavities in the foundation

b) sole foundation

Sole of foundation block should be in a horizontal plane. If fulfilment of this condition leads to excessive use of concrete, one of the two following solutions is allowed:

- replacing a portion of the soil with wedge of bedding concrete, however, it is not advisable that part of the sole foundation based on the concrete represents more than 5% of the sole surface (Fig. 4.12.a),
- cavity on a small area of the sole in the form of a run-down well from the bottom of the trench and separated by movement joints from the solid of the foundation; surface of such cavity should not be greater than 15÷20% of the surface of the foundation base (Fig. 4.12.b).

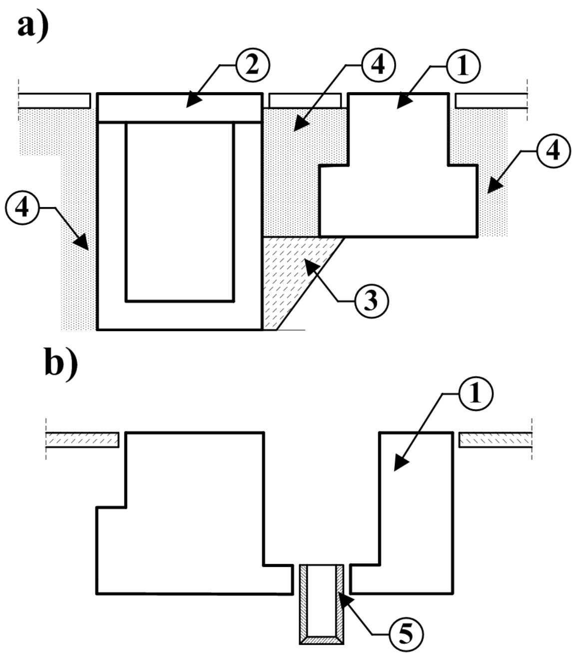


Fig. 4.12. Construction of the foundation in the case of differences in levels of foundations: a) replacement of the fill soil with the concrete under the foundation of the machine with deeper foundation of the object, b) the method of execution of local depression under the foundation base; 1– the foundation, 2 – cable channel, 3 – concrete C 8/10, 4 – compacted embankment, 5 – run-down well (Lipiński 1988)

4.6.4. Anchoring of machines in block foundations

The bolts in block foundations are typically placed in special wells, which are formed during construction of the foundation.

There are two basic types of fixing the foundation bolts:

a) with permanent concreting,
b) enabling the screw removal.

Different types of fixing bolts according to both above methods are shown and described in Lipiński (1998).

4.6.5. Design of foundations in plan

When determining the shape of the block foundation in plan, the following recommendations should be satisfied:

- shape of the foundation base should be adapted to the machine, where it should have a substantially rectangular base except when it leads to excessive use of construction materials or excessive enlargement of the foundation base,
- the foundation should be separated from adjacent foundations or structures and hall floor with a 2.0 cm expansion joint,
- foundations for machines with IV dynamic category should be moved away from adjacent foundation of at least 0.3÷0.5 m,
- centre of gravity of the foundation sole should be in the vertical line, passing through the centre of gravity of the overall system, consisting of the foundation and machine, and based on the foundation of installations, equipment as well as ground on the edges,
- where space is limited in the hall, it may be necessary to shape the foundation soles with the expansion of the overloaded side of the foundation,
- in special cases, it is allowed to use the cantilevers in foundations, which in general are not allowed in this type of structures.

4.6.6. Principles of reinforcement in block foundations

The reinforcements of foundation blocks under the non-impact machines usually are not calculated, but only adopted structurally. However, it should be remembered to check the serviceability limit state for scratching.

The amount of the required reinforcement in block foundations usually depends on excitation forces – F_d and the dimensions of the foundation, i.e.: length – l_f, width – b_f, height – h_f and volume – v_f.

The general requirements for the structural reinforcement of block foundations for non-impact machines are as follows:

a) block foundations for machines with a resultant of excitation forces $F_d \le 0.5kN$ and dimensions of the foundation: $l_f / h_f \le 5$; $v_f \le 20m^3$.

Such foundations are reinforced only on the periphery of holes, indentations and weak areas. The reinforcement is in the form of meshes with a size 15÷20 cm and bar diameter ϕ8÷ϕ12.

b) block foundations for machines with a resultant of excitation forces $F_d > 0.5kN$ and dimensions of the foundation: $l_f / h_f \leq 5$; $v_f \leq 20m^3$.

Such foundations are reinforced as in a) and additionally, bar diameter ϕ12÷ϕ16 with mesh 20÷40 cm, laid down in the planes of the top and bottom of foundation.

c) block foundations for machines with volume $v_f > 20m^3$; compacted foundation – $l_f / h_f \leq 5$.

Such foundations are reinforced as in b) and additionally, all remaining surfaces of foundation block with ϕ12÷ϕ16 bars and mesh 30÷40 cm. Also, spatial reinforcement with ϕ12÷ϕ16 bars with spacing of 60÷80 cm, arranged in three mutually perpendicular directions, should also be used.

d) weakly compacted block foundations $l_f / h_f > 5$

In the case foundations of this type, the required amount of longitudinal reinforcement arranged in the plane of the underside of the block – A_z [cm^2], it is determined from the following estimated formula:

$$A_z = \frac{Gl_f}{20h_f}, \tag{4.9}$$

where: G – mass of the whole system, i.e. foundation and placed on it machinery and equipment [Mg].

The reinforcement of the upper grid in the direction of length l_f should not be less than half of the bottom reinforcement. In addition, for all above cases, screw holes should be reinforced. The screw holes in foundations for machinery require reinforcement due to the ease of formation of cracks from concrete shrinkage in the areas weakened by them. Only in small blocks, with a small cubic capacity 1÷2 m^3 for machines of I and II dynamic category, the holes do not require reinforcement.

It is appropriate to reinforce holes for anchor bolts with the method shown in Fig. 4.13.a, which guarantees good anchoring of bars. The reinforcement of holes with the use of bars coiled in a spiral is sometimes used. This method is not preferred due to the poorer anchoring of bars in concrete. An attention should also be paid to the necessity of accurate reinforcement of screw holes, located near the edge of the foundation block. This is shown in Fig. 4.13.b.

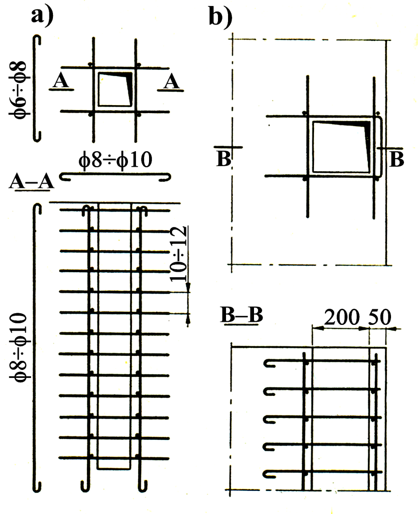


Fig. 4.13. Reinforcement of holes for anchor foundation bolts: a) at a distance from the edge, b) at the edge of the foundation

4.6.7. Scope of calculations of block foundations for non-impact machines

Taking into account all the guidelines and principles when designing block foundations for non-impact machines, the scope of design calculations includes:

a) verification of the ground pressure,
b) verification of the position of the centre of gravity of the foundation with the machine with respect to the centre of gravity of the foundation base,
c) verification of strength of particularly weak points of the foundation structure,
d) verification of natural frequencies and amplitudes of forced vibrations of the foundations,
e) verification of the dynamic conditions according to the criteria described in Ch. 2.

4.7. Block foundations for hammers

4.7.1. Structure of foundations for hammers

The dimensions of foundation block is determined on the basis of structural conditions as well as soil and local conditions, and then it is checked by calculation of vibration amplitudes, pressure on soil and influence on the environment. Initially, mass of foundation – m_f is assumed depending on the mass of falling parts – m_0 according to the following formula:

$$m_f = 70 \div 80 m_0 . \qquad (4.10)$$

The minimum height of the foundation block under the anvil – h_k (Fig. 4.14.) also depends on mass m_0 and must be taken according to Tab. 4.4.

Table 4.4. Minimum thickness of the block under the anvil according to Lipiński (1988)

Mass of falling parts m_0 [Mg]	Height of the block under the anvil h_k [m]
< 1.0	1.0
1.0÷2.0	1.25
2.0÷3.0	1.50
3.0÷4.0	1.75
4.0÷5.0	2.0
5.0÷6.0	2.25
6.0÷10.0	2.60
> 10.0	> 3.0

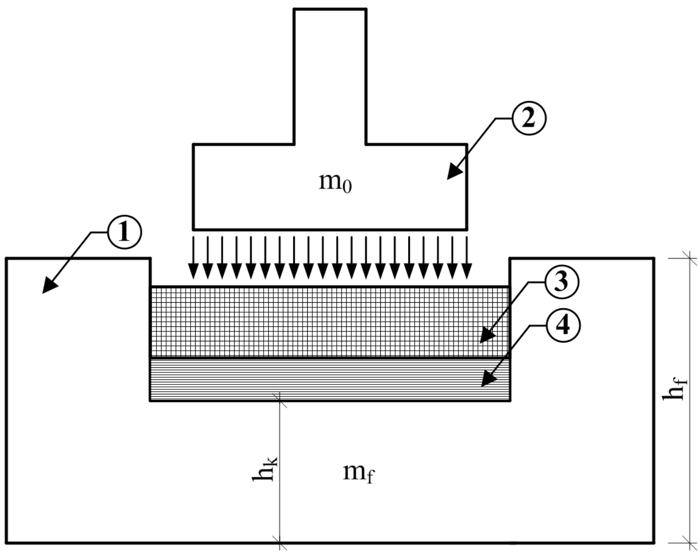


Fig. 4.14. Scheme of load of the foundation for the hammer; 1– the foundation, 2 – the hammer, 3 – the anwil, 4 – elastic washers

4.7.2. Scope of the calculations of block foundations for hammers

The dynamic loads in foundations for hammers are impulses with high values occurring when the beater hits the anvil (Fig. 4.5. and 4.14.).

The exact dynamic calculation of the system consisting of the hammer and foundation is very complicated due to the fragmentation of masses. In a large hammer with the energy greater than 150 kH, the anvil consists of 2÷3 non-connected parts and the body of the hammer consists of two parts connected with each other with springs. All of these parts, along with a block foundation and vibration-isolators, moving under the influence of the impact, interact with each other, making it difficult to conduct traffic analysis.

The rules for load determination in hammers are given in Ch. 4.3.4. Below is the algorithm for calculations of foundation block for hammer, which consists of the following steps:

a) verification of the ground pressure,
b) verification of the position of the centre of gravity of three elements, i.e.: sole, foundation system – anvil and impact beater,
c) verification of the vibration amplitudes,
d) verification of the load capacity of anvil washer,
e) verification of the capacity for puncture,
f) calculation of required amount of reinforcement in the foundation.

4.8. Vibration isolation of foundations for machines

4.8.1. Tasks and basic vibration isolation systems

Vibration isolation is based on the use of appropriate spring elements, placed between the source of vibrations and the protected object, for protection from harmful effects of vibrations. The use of vibration isolation in foundations for machines is designed to:

- protect the environment from vibrations generated by the machine (active vibration isolation) or,
- protect sensitive devices from vibrations transferred through the ground of the room, in which the equipment is to be located (passive vibration isolation).

Both types of vibration isolation in the foundations for machines are characterised as follows:

a) active vibration isolation

It is intended to reduce the effects of excitation forces generated during the operation of the machine, transferring them to the subsoil or support structure in the form of disruptive forces limited accordingly.

b) passive vibration isolation

It aims to reduce the influence of vibrations of the ground or the support structure, transferring the forcing vibrations on the machine with respectively limited amplitude.

When setting the foundations on a single vibration-isolator, there are two major **structural systems**, i.e.:

a) supported system – foundation block is directly set on shock absorbers or when using continuous elastic washers

This system is used: when setting the machines on floors, with foundations for non-impact machines, high-speed with well balanced excitation forces, etc.,

b) suspended system – foundation block is suspended on shock absorbers.

The system, compared to the supported system, is characterised by certain advantages in the range of: ease of access, maintenance, durability of shock absorbers. This system requires less space in plan for the entire device, is closer to the ideal state of the solid freely suspended in space.

4.8.2. Types of vibration-isolators

Vibration isolation measures can be divided into different types of **elastic washers** and **vibration-isolators**. Spring washers under the foundations are usually made of slabs: cork, rubber and rubber-like materials. The vibration-isolators are different types of steel springs or single pads of rubber or cork.

When taking into account all available vibration isolation measures, it can be stated that the basic types of vibration isolation include:

a) steel springs:
- cylindrical bolt,
- leaf
- disk,

b) rubber vibration-isolators,
c) cork slabs,
d) viscous dampers,
e) special spring washers, e.g. shredded cork with a polymeric binder
f) special anti-vibration structures, e.g. roller vibration-isolators.

4.9. Framework foundations

4.9.1. Characteristics of framework foundations

Framework foundations consist of three structural elements, i.e.:
- **bottom slab** of large thickness, transferring the loads to the subsoil,
- **columns** fixed in the bottom slab, supporting a top slab,
- **top slab** – constituting a direct support for the machine – which is constructed as a system of intersecting transverse and longitudinal beams, usually in the form of grillage.

The spatial structure (Fig. 4.15) formed in this way is an arrangement of elements performing flexural-torsional vibrations under dynamic loads in contrast to the block foundation considered as a rigid solid vibrating on the elastic substrate. Such foundations are usually for high-speed machines, i.e. turbine sets.

In most cases, framework foundation is designed in such manner that the space between the bottom and top slab is used to carry out the installation or for media inlet and outlet. Often, other devices are located in this zone; necessary for the proper functioning of the machine or assisting in its work (Fig. 4.15).

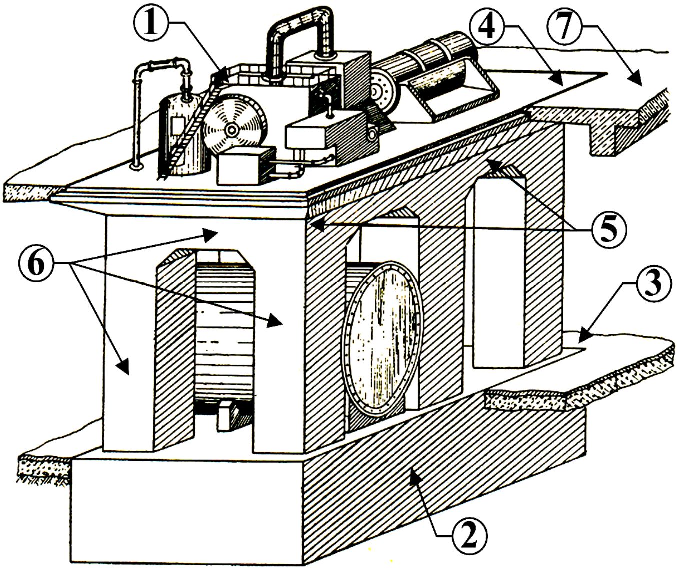


Fig. 4.15. Framework foundation for machine (Kral 1973); 1 – the machine, 2 – bottom slab of the foundation, 3 – bottom floor of the room, 4 – top slab of the foundation, 5 – longitudinal beams, 6 – transverse frames, 7 – ceiling of the machine hall

4.9.2. Structural recommendations related to framework foundations

When determining the shape and dimensions of the framework foundation, the following recommendations should be satisfied:

a) mass of the top part of the foundation

In practice, it is assumed that the vibrating mass, consisting of the masses in the top 1/3 height of the frame part (top slab, some of the columns and those parts of the machine, which are based on the top slab and are rigidly connected), should be 10÷15 times greater than the mass of the rotors.

b) dimensions of the cantilever section of the foundation

With the overhang not greater than 1.0 m, slab cantilevers can be used, while in the range 1.0÷1.5m – ribbed cantilevers. Generally, cantilevers with an overhang greater than 1.5 m should be avoided, in the case of necessity of their use, it is essential to thoroughly check the cantilever in terms of dynamics. The beams in cantilever sections of the foundation should be at least 40cm high, and this height should be approximately 1/8 of the cantilever span.

c) dimensions of the basic elements of frame structure

The minimum dimensions of the column depend on the power of the turbo generator and are in the range from 0.3 x 0.3 m for small machines, with capacity up to 1.5 MW, to 0.8÷1.0 x 1.0÷1.5 m (greater dimension in the transverse direction) for machines with power of over 100 MW.

The height of the beams – *h* consisting of top slab of the foundation should fulfil the condition:

$$h \geq 0{,}8l^2, \quad (4.11)$$

where: *l* – span of the beam [m].

d) foundation system

The foundation should be simple, symmetrical with respect to the longitudinal axis. All columns of frames should be of square or rectangular cross-section, which is justified by structural reasons and columns of longitudinal frames should be in one plane.

The beams of frames should be similar to rectangular shape with the necessary notches or openings. The axes of beams should be in the axes of columns.

The loading with parts of machine should be transferred to beams possibly axially to minimise the torsion.

e) the haunches at the intersections of structural elements of foundations

The haunches are desirable in order to increase rigidity of the system and to ensure a better distribution of stresses when changing the section.

The dimensions of haunches depend on the dimensions of intersecting elements and in average range from 0.3 x 0.3 m to 0.5 x 0.5 m.

4.9.3. Principles of reinforcement of framework foundations

The following summarises the most important requirements for the reinforcement of individual elements in the framework foundations.

a) reinforcement of beams (transoms) forming a top slab.

The top slab of the foundation is formed of longitudinal and transverse beams with a complex cross-section due to the notches, channels and openings. This makes it difficult to obtain a fairly regular arrangement of reinforcement and necessitates the use of bars of complicated shapes. The presence of steel elements concreted in the foundation (cantilevers, casing pipes of anchor bolts, bearing plates) makes it necessary to decrease the spacing of bars or arrange them in several layers. Large cross-sections of beams require, even at minimum reinforcement, the use of a relatively large number of bars, which hinders their arrangement.

With the reinforcement of beams, the bars should be of simple shape and the full height of the cross-section should be used. Therefore, the reinforcement should be placed in the lowest and highest part of the beam.

Often, in longitudinal beams, it is necessary to lay down the main reinforcement below the bottom of the channel and to treat certain beams between the channels above this reinforcement as not working concrete overlay, which should be structurally reinforced with the mesh consisting of $\phi 8 \div \phi 10$ bars with spacing 5÷25 cm.

The main reinforcement should be laid in such a way to facilitate pouring of concrete mix (use distances greater than the minimum); this particularly regards to top layers of reinforcement, among which the vibrators compacting the concrete mix are placed. It is preferable to lay bars in two or even three layers, leaving suitable gaps between bars. The bars of particular layers should be laid one above the other.

It should be remembered to reinforce corners of beams for shear; stirrups or stirrups with bent away bars are used and torsion; stirrups and longitudinal bars are used. The stirrups should not be larger than 8÷12 mm and their spacing should not exceed 30 cm.

b) column reinforcement

Columns should be reinforced with longitudinal bars arranged symmetrically. Minimum reinforcement of columns consists of ϕ16÷ϕ20 bars at 20÷25 cm.

Stirrups should cover every 3 or 4 bars of longitudinal reinforcement and their diameter should be 8 mm. Typically, four-arm stirrups supplemented with "pins" are used. The spacing between the longitudinal bars and stirrups should not exceed 25 cm.

c) reinforcement of the bottom slab

The reinforcement of the bottom slab should be in the form of two meshes, arranged at the top and bottom surface of the slab. The meshes should consist of ϕ16÷ϕ30 bars wit the mesh 20 cm. Additionally, anti-shrinkage reinforcement with ϕ12÷ϕ16 bars at 30÷40 cm should be used.

4.10. Support structures for machines

The support structures for machines are special structures that transfer static and dynamic loads, and which cannot be clearly classified into groups of block or framework foundations.

The support structures for machines include:

a) ceilings loaded dynamically,
b) free-standing platforms loaded with machines,
c) support structures fixed to walls or columns of a building loaded with machines,
d) other structures lifting machines, and not having the character of the block or framework foundations, for example reinforced concrete channels of circulating water, on which the pumps are set.

The scope and sequence of conducting dynamic calculations of support structures for machines depend primarily on:

- the type of analysed support structure,
- the dynamic character of the operation of machine.

4.11. Conditions for implementation, operation and maintenance of foundations for machines

4.11.1. Comments on the construction of foundations

When constructing foundations for the machine, the following rules should be observed (PN-EN 13670 2011):

- concrete of the foundation block should be of the highest possible quality, which requires the use of ingredients (for its construction) of proven high quality,
- the composition of the concrete mix should always be designed by a professional technologist and verified with laboratory tests,
- it is required to use coarse aggregate – broken, originating from volcanic rocks,
- aggregate grain size should be in optimal field, between the border grain size curves. It is unacceptable to use gravel sand and uncontrolled grain size,
- it is desirable to use slow-setting cements with low bonding temperature, optionally with addition of chemicals retarding the setting of concrete mix,
- foundations should be concreted in accordance with specially designed program using vibrators and without breaks when concreting,
- immediately after concreting, the surface of the foundation should be smoothed. It is important to obtain a horizontal, flat and smooth surface immediately after concreting of the foundation block as subsequent levelling or filling the surface with the cement mortar may be a source of damage. The accuracy of the foundation surface should correspond to the tolerance in the form of deviations from the levels in each direction, not more than 1.5 mm/m,
- if in the hall, where the foundation is concreted, the equipment causing strong vibrations is operating, it should be stopped for time of concreting and 24 hours after its completion,
- curing of concrete after concreting the foundation should be particularly careful, e.g. the niche for the anvil in foundations for hammers should be filled with warm water and all concrete surfaces should be maintained wet.

4.11.2. Guidelines regarding exploitation and conservation of foundations for hammers

Similarly to a machine, which must be regularly conserved by fixing, cleaning and lubricating, foundation also requires a proper treatment. Any negligence in this field can cause foundation damage difficult to repair and consequently may lead to its destruction (Runkiewicz 2011). The overview of possible faults and damages that may occur as a result of the occurrence of dynamic loads generated by machines is shown in Ch. 3.2.1. Below, in several groups, the most important guidelines regarding the proper inspection and maintenance of foundations for machines and vibration isolators are summarised.

a) general guidelines for the maintenance of foundations for machines

The works on the maintenance of foundations should be performed periodically when the machines are not working, e.g. when replacing the matrices in case of hammers. In order to verify the correctness of the foundation and to control the support of the machine on the foundation – during the first two months after the start-up of machines – inspections should be conducted once a week. Later, after gathering relevant experiences relating to work of the foundation, the period between inspections may be longer. The breaks between inspections should depend on the actual need, however, they should not exceed one month.

In the structure of machines, any changes are not allowed as this could increase the dynamic loads transferred to the foundation.

b) cleaning the inside of foundation

All residues after carried out technological processes, e.g. scale, sawdust and possibly other objects, which fell in the vicinity of the foundation should be removed.

With particular accuracy, all the cavities and openings in the foundation should be controlled, e.g. cavities for anvil head in the foundations for hammers.

Any objects and devices, which could slow down the freedom of movement of these foundations should not be in the area of block foundations and bottom slabs of framework foundations.

The correctness of the operation of system draining the bottom section of foundations should be checked. The accumulation of water in the area of foundations and flooding of parts of machinery should not be allowed to happen.

c) protection of the foundation against oiling

The locations of foundation, where the technical oils and lubricants may get – adversely affecting the concrete – should be protected with suitable covering, mortar or paint, e.g. with liquid glass. Sheet metal gutters or pipes carrying off oil out of the foundation.

The locations where oil penetrates into the foundation block can be wells for anchor bolts. The protective pipes and the wells filled with cement mortar prevent penetration of oils and grease into the interior of the foundation.

d) vibration-isolator control

In the foundation with vibration-isolators, their location should be controlled, and if the location changes, the vibration-isolators should be slid into the place.

The condition of springs and rubbers in rubber vibration-isolators should be very carefully checked. Any damages of vibration isolators should be removed immediately. If cracks in the springs have been observed, they should be replaced with the new ones with the same characteristics.

5. Reinforced concrete crane beams

5.1. Crane transportation in industrial plants

5.1.1. Transportation within industrial plants

Transportation related to operation of industrial plants can be divided into:

- **outdoor**, which includes roads, railways, water and other giving the opportunity to transport materials and semi-finished products on the area of industrial plant and to pick up elements that are a final stage of the manufacturing process,
- **indoor,** which includes transportation, handling and storage of raw materials, semi-finished products and fabricates on the plant area, in production halls, stockpiles and buildings associated with the manufacturing process, e.g. in steel yards in precast concrete plant.

The main impact on the technological process design as well as type and location of objects in the industrial plant has a type of indoor transportation. Routes and communication devices in industrial facilities are: stairs, ramps, slides, lifts, while the transport devices include e.g.: **cranes**, conveyors, trestle bridges, loading bridges, pneumatic transport, suspension railways and others.

The most commonly used devices for indoor transportation in industrial plants are cranes. Cranes are machines, which are used to transport load horizontally and vertically within the limited range. When lifting, maintaining at rest and moving loads on crane runway (through pressure of its wheels) act forces: vertical, horizontal and longitudinal. The values of acting forces depend on the size of the transported weight and position of the crane wheels on the track. These forces cause: bi-directional bending, torsion, compression or tension of the crane track supporting the crane. The main types of cranes are: overhead cranes, turntables, tipplers, cantilever, building cranes, suspended monorail crabs, elevators and others.

5.1.2. Types of overhead cranes and their use

Crane composes of a moveable structure and travelling along it hoist block or crab. It transports the load within the space limited by the lifting height, extreme positions of hoist block or crab and extreme positions of the crane. Cranes can be controlled from the working level of the hall or storehouse, from the cabin or remotely (wirelessly). In industrial plants, for material and element transportation, the following cranes are used: overhead travelling, semi-portal bridge, gantry, bridge or cantilever. The most common type of crane in large manufacturing halls, on bridge trestles, in warehouses and storage yards – are **overhead travelling cranes**.

Overhead travelling crane is a machine designed for lifting and moving loads, which travels on the runway beam. It is equipped with one or more crabs with built-in hoists moving on the rails or on bottom flanges of the crane bridge. Scheme of double-girder, single-hook overhead crane is shown in Fig. 5.1.

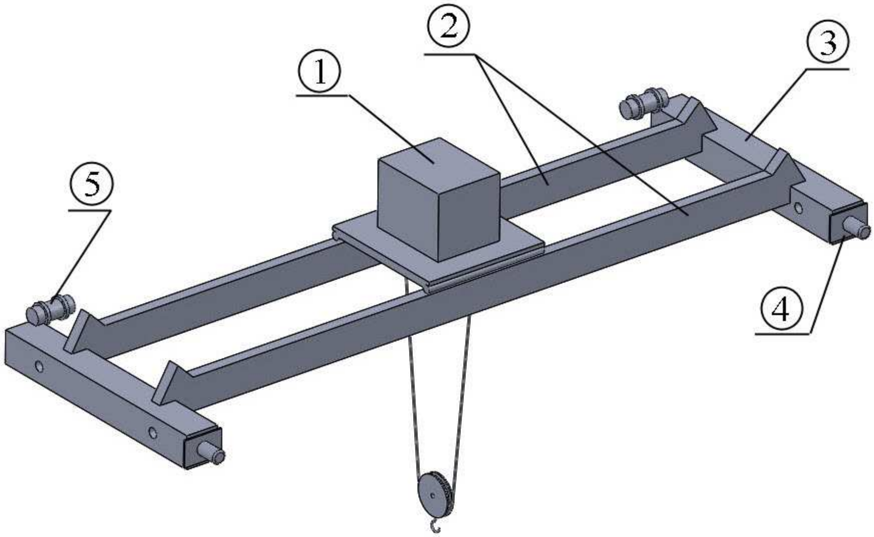


Fig. 5.1. Diagram of double-girder overhead travelling crane; 1 – crab with hoist, 2 – crane bridge girder, 3 – front beam, 4 – bridge drive, 5 – bumper

Crane transport is possible by means of the following three mechanical systems of which each has a separate drive and is controlled separately:

- the bridge crane drive,
- the crab drive,
- load lifting.

To ensure failure-free crane operation, it is necessary to properly design a special runway beam, on which it will travel (see Ch. 5.1.3.). Such runway beams require adequate structure, which depends on the workplace.

In the case of cranes working in closed halls, runway beams are most often located above ground, above the weight lifted by the crane and fixed to two parallel runway beams supported on columns or walls. On runway beams located are specially fixed rails used as guides for wheels. The distance between the axes of rails corresponds to the track width and is the span of the overhead crane.

In the tracks located on the ground or floor level, they are based on the substrate (consisting of railway sleepers on ballast) or on permanent foundation (in the form of two longitudinal concrete strips).

If the crane will be working on an open site, it is necessary to design appropriate structures (trestle bridges). Trestle bridges usually feature columns and supported on them runway beams, on which placed are crane rails. This solution is also used when the same crane is to work in the hall and adjacent storage yard. The outdoor runway beam is the extension of the internal runway beam.

5.1.3. Devices of overhead travelling cranes

The main element of each overhead travelling crane is called a **crane bridge**, which is a part of the crane spanned between runway beams and the crab or hoist block. Crane bridge can be one-girder (Fig. 5.2.) or two-girder (Fig. 5.1.).

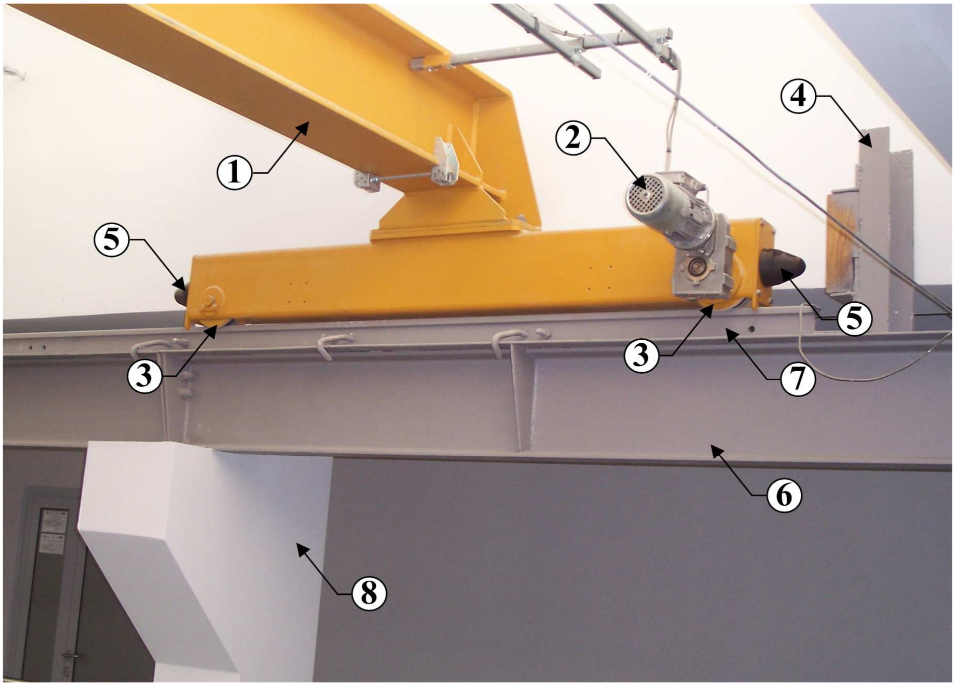


Fig. 5.2. Detail of the crane bridge support on the steel runway beams; 1 – crane bridge, 2 – motor, 3 – crane wheels, 4 – buffer, 5 – bumper, 6 – runway beam, 7 – crane rail, 8 – column with a short cantilever (photo by author)

Two-girder bridge consists of two parallel solid or lattice girders, connected together in a rigid manner. Near the connections located are wheels enabling the movement of the bridge. The space between girders should remain free, so that the crab with the hoisting device could move freely. Runway track for hoist block can be on top and bottom flanges of the crane bridge. The crane bridge is supported on the runway beams most often through four, sometimes eight wheels. Typically, one pair of wheels is driven by the electric drive. The detail of the crane bridge support, on the example of crane moving on steel beams, is shown in Fig. 5.2. The crane bridge speed ranges from 1.0 m/s for large-span cranes, e.g. 21.0 or 24.0 m to 2.0 m/s for smaller size cranes, e.g. 9.0 or 12.0 m.

Hoist block, which is an element of overhead travelling cranes, is an underslung crab with a built-in hoist, which travels on the flange of the crane bridge. The crab movement is perpendicular to the runway beam and its drive is electric.

Hoist is a device that has a drive mechanism for lifting, lowering and transporting loads within the crane capacity, i.e. its allowable capacity specified by the manufacturer. The hoist is an electrically driven device, equipped with a drum and a rope system with sling hook (gripper). With the help of the hoist, the lifted loads can be transported anywhere in three-dimensional space of the hall or storage yard.

The most important structural element of the entire crane load bearing system is the runway beam track. **Runway beam** consists of the crane beam and crane rail. It should be properly designed and precisely constructed, because through this element loads from wheels are absorbed first by crane beams and then the entire support system of the hall or trestle bridge.

Crane beam is a structural element of the industrial hall. It is the main track on which the crane travels. It takes vertical loads (from the pressure of wheels and uniformly distributed self-weight) as well as horizontal loads (from cross-braking of the crab, side impacts of the wheels and longitudinal braking of the crane bridge). Its task is to transfer all loads resulting from the operation of crane on structural elements of the hall, which most often are: columns with short cantilevers or pilaster columns and pocket foundations.

Crane rails (Fig. 5.2.) can be made of special profiles, rails or replacement profiles in the form of a square or rectangular section welded to a flat plate. The selection of an appropriate rail profile depends on the pressure of wheels and stresses, which may occur in the cross-section of the rail, e.g. (Euler, Kuhlmann 2011). The most economical are the railway rails, which are characterised by high stiffness. The details of methods and procedures for connections of crane rail with the runway beam will be described in Ch. 5.1.4.

Important structural elements of crane beams from the point of view of crane safety are **buffers** and **bumpers**. Their role is particularly important during the occurrence of accidental loads (see Ch. 5.4.).

Buffer stops installed at the ends of crane beams (Fig. 5.2) should absorb the impact force of the crane, caused by improper operation or failure of control equipment of the crane. On the other hand, cranes moving on crane beams should be equipped in rubber, spring or hydraulic bumpers (Fig. 5.2). In addition, wedges may be used that reduce the kinetic energy of the impact (slope 1:5). In the absence of data, it is assumed that the horizontal impact force of the crane against the buffer is equal to the pressure of the crane wheel.

Dimensioning of the buffer stops of the crane should be carried out in accordance with the plasticity theory in such a way that the buffer stop during the impact absorbs its effects and undergoes a plastic deformation, but was not rigid.

5.1.4. Devices of overhead travelling cranes

Connection of rail with the crane beam is one of the most important issues in runway beam design and their construction. Analyses of proper cooperation of beam and rail for years have been the basis for model tests and theoretical analyses, e.g. the vulnerability assessment of connection of rail with crane beam. The connection of crane rail with beam is very important as its improper construction may later lead to concrete spalling in the beam and adversely affect the work of the entire hall structure or trestle bridge. Errors resulting from improper design or connection of rail with crane beam are one of the major faults that have been observed in the crane track structures. Errors of this type are usually the cause of repairs of these structures and their subsequent frequent maintenance.

Proper fixing of rail to the crane beam must meet the following conditions:

- crane rail should be free from deformations and deflections,
- mounting elements should transfer from the rail to the beam vertical compressive, tensile and horizontal forces taking into account the allowable compressive concrete strength,
- rail arrangement should be such that it is possible to damp vibrations transferred to concrete, resulting from the operation of the bridge and crab,
- rail should be fixed in such a way to have freedom of movement in the longitudinal direction, due to thermal expansion and concrete shrinkage.

Connections of rails with crane beams can be divided into: fixed, spring, movable and flexible.

With **fixed connection**, used only in small capacity crane beams, it can often lead to concrete crush or damage in the upper zones of the beam. The connection is done by welding the rail to the plate, which is connected to the beam with the use of anchors.

Spring connection gives the possibility of longitudinal movement of rail in relation to the crane beam. They are obtained using pads, which absorb and evenly distribute the wheel pressure on the beam. Pads of this type are most often the specially fitted wooden elements or cement screeds. The solution of this type gives the possibility to lay and easily regulate rail positions, while its disadvantage is a significant total height of the crane track causing an increase in torsional moment of runway beam.

A preferred solution of connection of rail with runway beam, which is often used especially in RC crane beams, is a **movable connection**. Such a connection is realised through steel plate pads, spaced at 0.5 m or continuous steel plates. The rail, which is positioned on the pads, is fixed to the crane beam with screws or special steel clamps.

Currently, crane suppliers also offer innovative solutions of **flexible connection** of rail with the crane beam. Flexible fixing of rails to crane beams, as schematically shown in Fig. 5.3 (Golewski 2012):

- reduces the costs of repairs and maintenance of the crane track,
- reduces adverse stresses in the cross-section of rail and beam,
- reduces vibrations and noise,
- ensures the possibility of adjusting the rail's position during and after assebly,
- eliminate damages that can occur in traditional connections of crane track, e.g. immovable,
- high strength of fixing clamps (Fig. 5.3.) for lateral forces.

Connections of this type (Fig. 5.3.) consist of several separate elements and are realised according to the following scheme:

- **rails –** take the loads from cranes and through the connection they transfer them to the crane beam,
- **flexible pads –** form a shock-absorbing substrate on which the rail is based; available are two technical solutions: a continuous elastomeric tape placed over the entire length of the rail (in the case of high lifting capacity cranes), elastomeric rail pads arranged in the form of short sections on membered plates (in the case of small capacity cranes),
- **fixing clamps –** maintain the rail in the proper position on the crane beam and allow for precise side adjustment of the rail; clamps are fixed to the substrate by welding to the lower part or by fastening screws,
- **membered plates –** small low-alloy steel plates, which are placed under the rail in certain spacings (typically about 0.5 m) supporting it in a discontinuous manner,
- **anchoring –** most commonly used in the form of threaded rods and matched to the specific type of washers or articulated plates and type of substrate,
- **non-shrinkable "screeds" –** in the form of Portland cement with mineral additives and chemical admixtures; it is to stabilise the substrate under the rail, which ensures high accuracy of the connection.

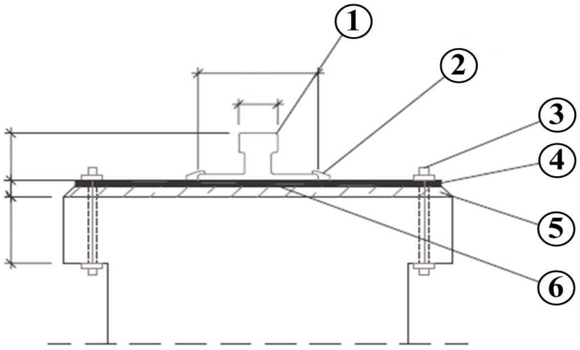


Fig. 5.3. Scheme (cross-section) of elastic connection between rail and runway beam; 1 – crane rail, 2 – fixing clamp, 3 – anchor bolts, 4 – membered plate, 5 – cement screed, 6 – elastomeric washer (dimension in mm)

5.2. Specificity of work of crane beams and their types

5.2.1. Crane beams in industrial construction

Crane beams belong to structural elements of industrial construction. Due to the transfer of significant loads of dynamic character, they require experience in designing and reliable construction.

It should be emphasised that steel, reinforced concrete and prestressed crane beams require – beyond proper design calculations – very pedantic adherence to technical conditions such as: geometric dimensions, allowable tolerances with respect to the support and partial fixing on supports, axial arrangement of correct clearances between the longitudinal axes of beams and rails, axial and symmetric arrangement, and fixing of rails on beams, making the work of rail independent from the operation of runway beam, etc.

Any deviations from established computational schemes and inaccuracies during installation may result in additional, unforeseen in the design, stresses compounded by the dynamic nature of the work of cranes. Such situations may in result cause premature damages and the need for repairs of crane beams (Kobiak, Stachurski 1987).

Selection of the right variant of the beam is very important. The main factors determining the choice of beam type are most often the clear span of hall's columns, on which the beam will be supported or lifting capacity of the crane and its characteristic (weight of the crane, distance between the wheels along the crane beam, clear span of crane's frame, work cycles etc.). In addition, the designer should keep in mind other factors that may influence the choice of beam which include: characteristics of the warehouse or industrial hall for which beam is designed (prevailing environment, exposure class), the predicted lifetime of the hall, the likelihood of additional loads (related e.g. with the possibility of explosion or fire) and others.

Crane beams should be an element of the crane device, providing efficient transportation for the given hall or warehouse and hence the selection of the beam type and its design should strive to provide the best working conditions of the crane. Beams used in the industrial and warehouse construction are:

- monolithic reinforced concrete beams,
- precast reinforced concrete beams,
- steel beams,
- prestressed beams.

The following subchapters describe all kinds of crane beams.

5.2.1. RC monolithic crane beams

Monolithic RC crane beams are most often used for cranes with lifting capacity up to 200 kN, sometimes even 300 kN. Their use in the construction of crane beams is in many respects more preferable than the use of steel beams for this purpose as (Kobiak, Stachurski 1987; Starosolski 2016):

- due to a large massiveness (high inertia) they well carry dynamic loads,
- due to high stiffness, period of natural vibrations of crane beam is high in relation to the vibrations caused by the passing crane,
- are fire-resistant and can withstand even a few hours of intense fire in contrast to steel, which is subject to rapid deformations and loss of load capacity,
- are less sensitive than steel for non-axial arrangement of crane rails,
- do not require such a caring maintenance (anti-corrosion coatings, etc.), as steel,
- due to high stiffness they are elements well bracing the structure in the longitudinal direction.

The negative characteristics of monolithic RC crane beams are (Kobiak, Stachurski 1987; Starosolski 2016):

- heavy self-weight requiring strong columns and foundations,
- difficulties with damage repair and strengthening, when necessary, to install the crane with lifting capacity greater than originally anticipated,
- troublesome crane rails fixing.

The most common are beams with I-beam or L-beam cross-section, however, beams with rectangular cross-section are not used. This fact is linked to a number of advantages, which the structure of T- or L-section beams exhibit in comparison to rectangular beams. The most important ones include:

- high moment of inertia and stiffness for horizontal and vertical forces,
- easy fixing to crane rails,
- easy access during crane repairs.

The dimensions of cross-section of the crane beam highly depend on the span and magnitude of loads acting on it.

If the beam span is long and the crane lifting capacity is small, the cross-section is determined by the bending moment. In the opposite case, i.e. with high lifting capacity and short span, the cross-section is determined by the shear strength of concrete.

The height of crane beam varies typically in the range 1/6÷1/10 of its span, and in the range 1/2÷1/3 of the beam height. Thickness of the horizontal plate should be at least 1/10 of the beam height and at least 12 cm.

5.2.2. Prestressed crane beams

Prestressed crane beams due to increased fracture toughness and lower construction height may be considered as more favourable than the RC monolithic beams. The negative characteristic of prestressed beams is their smaller participation in longitudinal stiffening of the building, which is provided by monolithic beams connected with columns. In addition, these beams in comparison to RC beams are lighter and have better resistance to dynamic loads and repeatedly variable loads. A preferred characteristic of the prestressed crane beams with respect to the steel beam is, however, their higher stiffness and durability.

In the industrial construction, a number of types of prestressed crane beams were introduced, which replaced the steel or RC beam. They differed among themselves with load capacity and span. These were pre-tensioned and post-tensioned prestressed concrete beams (often assembled from segments) – with span of 6.0 or 12.0 m – prestressed with: wires, wire strands or cables.

Pre-tensioned prestressed crane beams

Pre-tensioned prestressed beams with a span 6.0÷12.0 m are used in the case of beams for lighter cranes. Currently, the following types of pre-tensioned prestressed girders are common (Ajdukiewicz, Mames 2008):

- BSFF-60/6 – with span of 6.0 m, cross-section height of 600 mm, mass of 2460 kg, with two variants of reinforcement (7 or 11 x 7ϕ5 mm),
- BSFF-90/6 – with span of 6.0 m, section height of 900 mm, mass of 4820 kg, with two variants of reinforcement, as above (Fig. 5.4.),
- SBP-90-12 – with span of 12.0 m, section height 900 mm, mass of 8500 kg, with two variants of reinforcement, as above.

Pre-tensioned prestressed beams are manufactured in specialised fabrication plants. Immediately after manufacture and after cutting the prestressing wires, they have a span of 592 or 1192 cm. Then, on the front beams applied is the protective layer of 2 cm thick fine-grain concrete, which makes that such girders are delivered to the construction site with the span of 596 or 1196 cm.

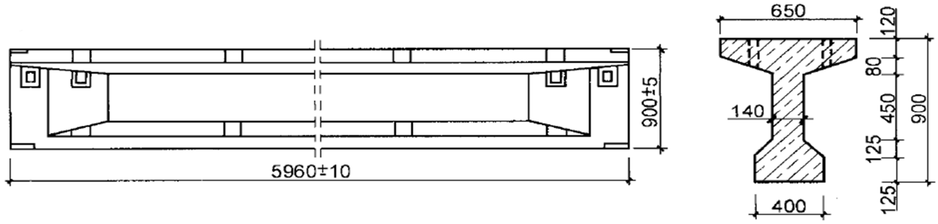


Fig. 5.4. Example of pre-tensioned prestressed crane beam of type BSFF-90/6 (dimension in mm) (Ajdukiewicz, Mames 2008)

Post-tensioned prestressed crane beams

Post-tensioned prestressed crane beams with span of 12.0 m are used in the case of cranes with higher lifting capacities. The following types of post-tensioned prestressed crane beams are used (Ajdukiewicz, Mames 2008):

- KBP-90-12 – with span of 12.0 m, section height of 900 mm, assembled from two or four segments, prestressed with straight cables 12ϕ5 mm in the number of 4, 6 or 7, with mass of 8950 kg or 9150 kg,
- KBP-120-12 – with span of 12.0 m, section height of 1200 mm, assembled from four segments, prestressed with straight cables 12ϕ5 mm in the number of 7, 11 or 14, with mass of 15000 kg (Fig. 5.5.).

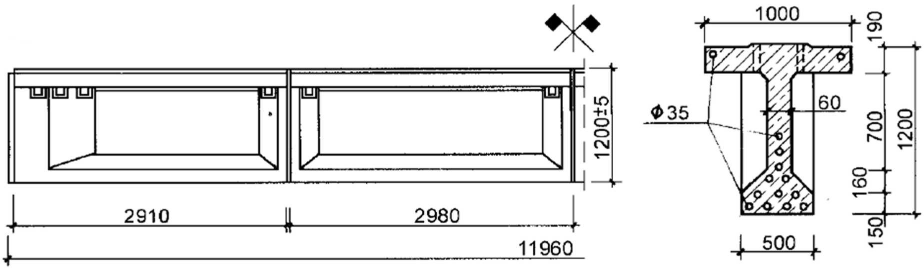


Fig. 5.5. Example of post-tensioned prestressed crane beam, assembled from segments of type KBP-120-12 (dimension in mm) (Ajdukiewicz, Mames 2008)

It should be added that a fundamental solution for KBP beams is their manufacture from two segments. The beams constructed from four segments are an alternative solution.

The elements of the beam are composited after completing the 2 cm thick joints made of cement mortar or mortar with polyester resin. The beam is prestressed mostly on the construction site as it is easier to transport individual segments than the entire beam. After prestressing and grouting the channels, on the front beams applied is a layer of fine, very tight concrete. This material protects tendon anchorage from corrosion. In addition, surfaces of joints of individual segments are protected from corrosion and chemical aggression. This operation can be done in two ways:

- by gluing a glass cloth and coating it with epoxy resin with a band width of 20 cm.
- by coating the surface of joints with epoxy resin (Kobiak, Stachurski 1987).

5.2.3. Steel crane beams

The following chapter will present general characteristics of steel crane beams and their basic types will be listed. More detailed information related to design and installation of steel crane beam can be found in the literature from the field of steel structures and steel industrial construction.

Steel crane beams are often and willingly used. Their advantages are lightness and speed of assembly, and they also offer great opportunity of repair in comparison with RC and prestressed beams. Obvious disadvantages of this type of structures include: need for corrosion protection, rapid loss of load bearing capacity under fire and lack of shear properties that RC beams have.

Crane beams are designed depending on the following parameters: planned span of the runway beam, lifting capacity, load capacity and stiffness requirements, specifics of their exploitation and structure of the system.

The following types of steel crane beams are as follows:

- solid-web without bracing,
- solid-web with checquer plate braces,
- solid-web with lattice brace,
- solid-web box,
- truss with horizontal brace.

Initially, the cross-section height of the crane beam – h is taken from the following condition:

$$h = l/10 \div l/12, \qquad (5.1)$$

where: l – span of the simply supported beam [m].

T-beam crane beams, rolled, strengthened or welded from plates without horizontal braces are designed with spans up to 9.0 m. In the case of cranes with small lifting capacity and girder span up to 6.0 m, rolled I-beam girders (HEB, HEA), not strengthened, can be designed. When selecting the girder cross-section, it should be remembered that in all types of steel crane beams, beam's top flange should be larger due to horizontal forces coming from crane's work. In the case of girders with span up to 9.0 m, it is required to design solid or lattice brake bracing.

5.3. Characteristics of precast crane beams

5.3.1. Beam cross-sections and their basic parameters

In industrial and storage halls as well as for trestle bridges, quite often used are precast RC T-beam crane beams. View of beam of this type, which is a part of the trestle bridge at the precast plant, shown in Fig. 5.6.

Fig. 5.6. View of precast RC crane beam; 1 – precast crane beam, 2 – two-branch column (photo by author)

Precast T-beam crane beams, as typified structural elements of halls are offered by plants producing concrete precast beams. Beams of this type are used as structural elements of industrial halls, warehouses and trestle bridges, in which the column spacing equals to 6.0 m. Depending on the lifting capacity of the crane beam, used are girders of type A, B or C differing with dimensions of cross-section and values of allowable internal forces. Within a given type there are three different beams with different degrees of longitudinal reinforcement. Typically, RC crane beams are made of C16/20 concrete class. Structural details of precast RC crane beams are shown in Fig. 5.7. They are also compared with other characteristic parameters, e.g. values of allowable internal forces for the given type of beam, in Tab. 5.1.

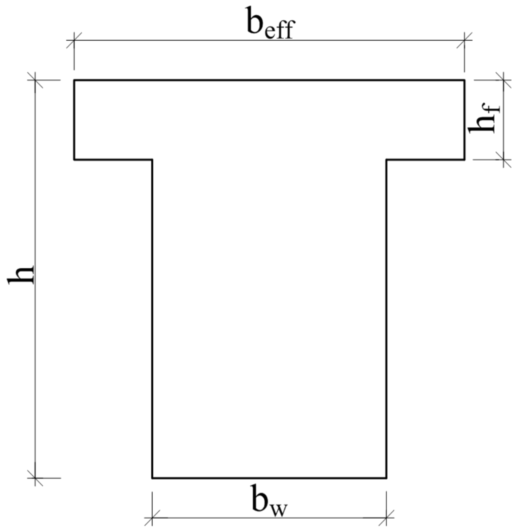


Fig. 5.7. Cross-section of RC precast crane beam

Table 5.1. Parameters of precast crane beams

Beam type	Dimensions [mm]				Allowable internal forces		Mass [kg]
	h	h_f	b_{eff}	b_w	M [kNm]	V [kN]	
A	400	120	450	200	83.9	67.8	1640
B	600	120	550	300	224.0	211.0	3120
C	800	120	650	500	744.0	551.0	6250

5.3.2. Basic advantages and disadvantages of precast beams

The choice of precast beams as structural elements in halls with crane transport is determined by the following advantages (Golewski 2012; Starosolski 2016):

- large massiveness, inertia and stiffness, which favours the transfer of loads repeatedly variable and dynamic,
- low sensitivity to fire and corrosion,
- greater resistance to concrete spalling around the anchor bolts of the crane beam in relation to the RC continuous beams,
- flexibility with the selection of construction type; they can be constructed on the hall's floor next to columns or in precast plants in reusable formwork.

The disadvantages of precast RC crane beams are:

- high self-weight,
- difficulty and often impossibility to reinforce damaged beams,
- bigger problems with fixing runways.

5.3.3. Assembly of precast beams

The combination of precast beams with supports, which are mostly short cantilevers or pilasters on columns, should be designed and constructed very carefully. This is because it must provide sufficient stability of the beam when exposed to transverse and longitudinal horizontal forces with respect to the direction of crane movement. Accuracy of connection requires the installation of crane rails, which can be laid only at the precisely levelled substrate. It should be kept in mind that the more precisely the beams are placed on the supports, the easier it will be later to fix the crane track.

Connection of the beam with supports is carried out in the following manner. To the plates anchored in columns with $\phi 10 \div 16$ mm bars, welded will be 50 x 50 x 6 angle sections near the support zone, previously concreted in beams and anchored in them using $\phi 10 \div 16$ mm anchors.

Before positioning beams on supports, bearing plates are usually placed on the underlay in the form of a fine grain layer of C16/20 concrete class. Such a treatment allows to smooth, usually almost unavoidable, inaccuracies in the construction of supports for runway beams (Kobiak, Stachurski 1987).

5.4. Loads acting on crane beams

Loads occurring in the crane beams are divided into three main groups:

a) occurring during normal operation of the crane, i.e. crane moving in a closed hall,
b) wind, acting on the load and crane – in the case of crane located on open space, e.g. moving on the trestle bridge,
c) unique – occurring sporadically when the crane hits the buffers.

Later in Ch. 5.4 more accurately characterised will be external forces acting on the crane beams located in closed halls.

During normal operation of crane beam, loads acting on the crane beams are divided into: **permanent** and **variable** (**temporary**, **technological**). Diagram of acting loads on one-span precast beam, with one crane moving, is shown in Fig. 5.8.

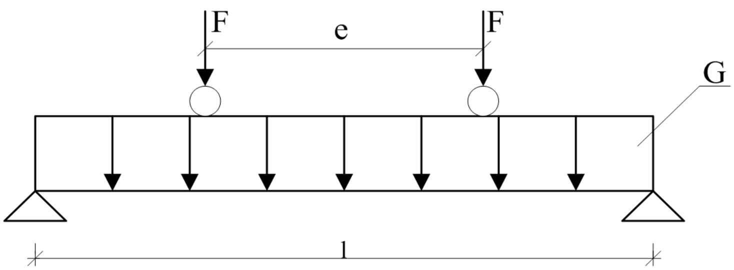


Fig. 5.8. Diagram of loading of crane beam; explanations of markings in text

On crane beams operating in halls may act the following loads:

- **permanent action** – G: self-weight of the beam and weight of crane beam (Fig. 5.8). This load generally in small impact affects the final value of maximum moments and transverse forces,
- **variable (live) action**: generally vertical and horizontal forces perpendicular and parallel to the crane beam (Fig. 5.9),
- **horizontal forces** – F: are caused by forces of gravity of the crane and the load – Q and dynamic loads, caused by crane operation. Vertical forces are acting at the joints of crane wheels with rails,
- **horizontal forces perpendicular to the crane beam** – H_{pk}: take into account side impacts, skewing of the crane and forces of inertia, generated during hoist's or hoist block's start-up or braking. These forces cause the occurrence of torsional moment in beam's cross-sections – T_{Sd},
- **horizontal forces parallel to the crane beam** – H_r: take into account forces of inertia generated during the crane's start-up and braking. These forces act at the contact points of all driven wheels with crane rails.

The directions of all discussed forces, acting on the crane beam, are shown in Fig. 5.9.

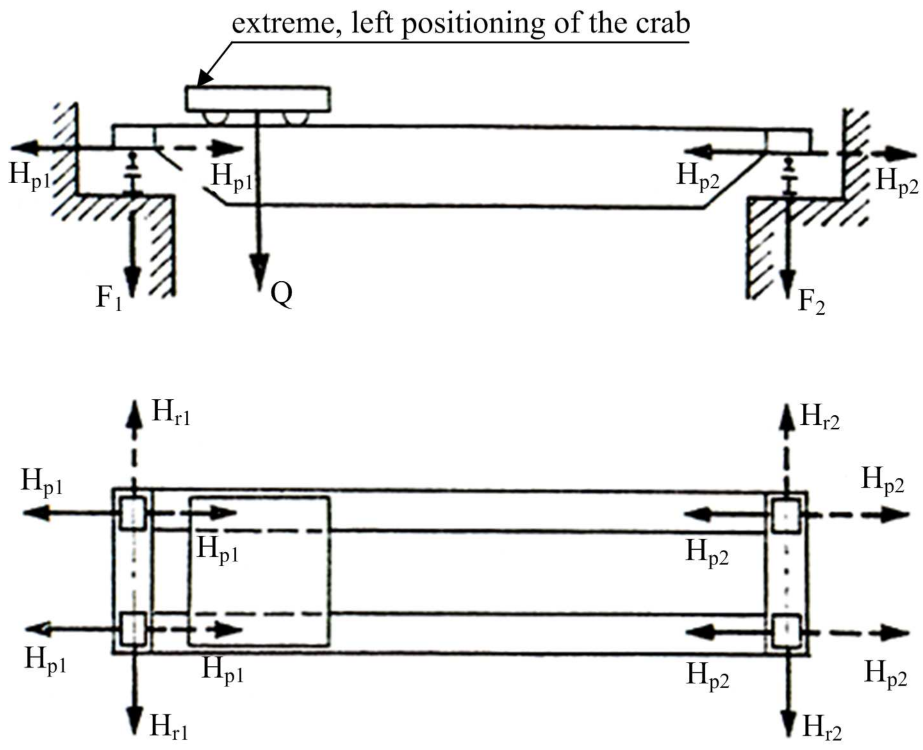


Fig. 5.9. Diagram of loading of crane beam; explanations of markings in text

5.5. Calculation of crane beams

5.5.1. Guidelines for determining internal forces

When calculating bending moments, transverse forces and necessary reinforcement in crane beams, a particularly high accuracy should be kept as they belong to the essential and very important elements of the industrial building.

When determining internal forces in crane beams, it is not sufficient to calculate the maximum value of bending moment in mid-spans and supports (in continuous beams), but it is also necessary (due to large moving point load) to find extreme values of bending moments in the intermediate points of the beam. Such a procedure allows for plotting an envelope of maximum negative and positive moments. Such a graph, including the stair-step graph of allowable transverse forces of beam, enables the design of proper bar deflection. an envelope is also prepared for maximum transverse forces, based on which additional reinforcement for major tensile stresses is designed.

5.5.2. The rules for determining loads according to PN-EN 1991-3 (2009)

In 2006, introduced was a new standard for design of structures loaded with cranes and machines – PN-EN 1991-3 (2009), taking into account the recommendations of Eurocodes. The current legislation with guidelines for crane beam design is a revised version of standard PN-EN 1991-3 from April 2009, which in accordance with the European Commission and the European Committee for Standardisation since March 2010 is the valid standard.

Standard PN-EN 1991-3 (2009) gives the models and representative loads caused by cranes on the runway beams. These loads include dynamic influences, braking and acceleration forces as well as accidental loads.

The actions caused by cranes are classified in the standard PN-EN 1991-3 (2009) as variable and unique.

Variable actions depend on the variability in time and position. They are divided into:

- **vertical** caused by the own weight of crane and lifted weight,
- **horizontal** caused by acceleration, deceleration or skewing of the crane, or other dynamic impacts.

Representative values of variable actions are characteristic values composed of static and dynamic portions. Dynamic components (resulting from forces of inertia and damping) are described by the dynamic factor φ applied to static values according to the following formula:

$$F_{\varphi,k} = \varphi_i F_k , \quad (5.2)$$

where: $F_{\varphi,k}$ – characteristic value of the action of the crane [kN], φ_i – dynamic factor, F_k – characteristic value of the static component of the action of the crane [kN].

Details of the dynamic factor values and their application are found in standard PN-EN 1991-3 (2009). The group of **accidental actions** that can occur during the movement and work of the crane includes: buffer forces as a result of collision between crane and buffers, and forces caused by deviation in the case of collision between gripping devices and obstacles. These actions relate to ordinary cases. They are represented by means of various load models in the form of equivalent static load, as a design value.

In the case of simultaneous occurrence of variable or special loads should be taken into account by the groups of loads in accordance with guidelines of standard PN-EN 1991-3 (2009) defined in Tab. 2.2. The selected design situations should be considered and the most unfavourable cases should be determined. For each most unfavourable case, design values of actions for combinations should be calculated.

For more complex design situation, e.g. multi-bay buildings with cranes, or several cranes working in one nave, standard PN-EN 1991-3 (2009) also provides solutions of how to take into account the complex actions of cranes or coupled cranes. Problems concerning the simultaneous actions of a higher number of cranes were also the subject of scientific publications. In these paper can be found e.g. analyses and models that describe how to take into account actions from cranes in the case of complex load patterns (Pasternak et al. 1996).

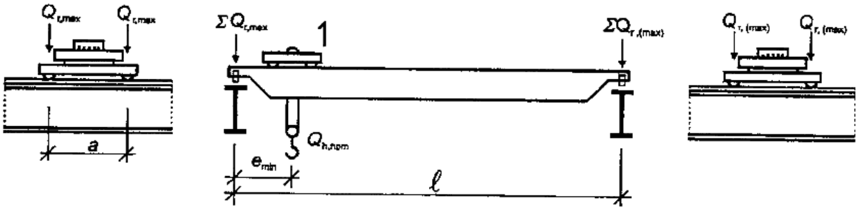
Crane wheels, as well as rolls and other guiding elements cause actions on crane beams that should be taken into account as vertical and horizontal loads. In order to determine these loads, the so-called **representation of crane actions** is taken into account. They present the position of bridge and crab, required for calculating the maximum and minimum loads, in the case of crane moving with or without the load. Arrangements to determine the actions of the crane are shown in Fig. 5.10 and are characterised below.

The eccentricity of application e of a wheel load $Q_{r,\max}$ to a rail should be taken as a portion of width of the rail head b_r . The recommended value is $e = 0,25 b_r$.

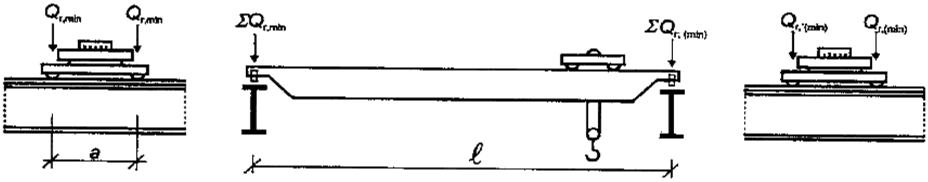
Characteristic values of vertical loads from self-weight of crane and weight of the lifted load should be taken based on the nominal values given by crane's supplier or calculated on the basis of standard PN-EN 1991-3 (2009). If dynamic factors are not given in the crane documentation, use the Tab. 2.4. from standard PN-EN 1991-3 (2009).

The group of normal forces that standard PN-EN 1991-3 (2009) recommends to consider includes:

- horizontal forces caused by the acceleration or deceleration of the movement of the crane along the crane beams,
- horizontal forces, caused by acceleration or deceleration of the movement of crab along the crane bridge,
- horizontal forces, caused by skewing of the crane in relation to its movement along the crane beams,
- buffer forces caused by the crane movement,
- buffer forces caused by the crab.



a) load arrangement of the loaded crane to obtain the maximum loading on the runway beam, 1 – crab.



b) load arrangement of the unloaded crane to obtain the minimum loading on the runway beam.

where:

$Q_{r,\max}$ – the maximum load per wheel of the loaded crane,

$Q_{r,(\max)}$ – the accompanying load per wheel of the loaded crane,

$\Sigma Q_{r,\max}$ – the sum of the maximum loads $Q_{r,\max}$ per runway of the loaded crane,

$\Sigma Q_{r,(\max)}$ – the sum of the accompanying maximum loads $Q_{r,(\max)}$ per runway of the loaded crane,

$Q_{r,\min}$ – the minimum load per wheel of the unloaded crane,

$Q_{r,(\min)}$ – the accompanying load per wheel of the unloaded crane,

$\Sigma Q_{r,\min}$ – the sum of the minimum loads $Q_{r,\min}$ per runway of the unloaded crane,

$\Sigma Q_{r,(\min)}$ – the sum of the accompanying minimum loads $Q_{r,(\min)}$ per runway of the unloaded crane,

$Q_{h,\text{nom}}$ – the nominal hoist load,

Fig. 5.10. Load arrangements to obtain the relevant vertical actions to the runway beams; 1 – crab (PN-EN 1991-3 2009)

Only one of the five types of horizontal forces is included in the same group of loads. The characteristic values of horizontal load should be taken on the basis of nominal values given by the crane's supplier or calculated using the standard PN-EN 1991-3 (2009). The main types of longitudinal forces are characterised below.

Longitudinal forces $H_{L,\mathrm{i}}$ and transverse forces $H_{T,\mathrm{i}}$ are caused by acceleration and deceleration of the crane (Fig. 5.11).

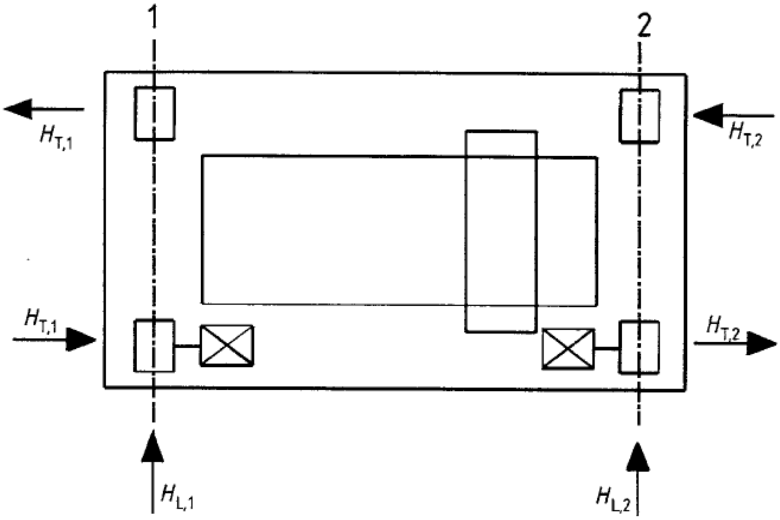


Fig. 5.11. Load arrangenlent of longitudinal and transverse horizontal wheel forces caused by acceleration and deceleration; 1 – rail i = 1, 2 – rail i = 2 (PN-EN 1991-3 2009)

The longitudinal forces $H_{L,\mathrm{i}}$ are caused by acceleration and deceleration of crane structures and result from the drive force at the contact surface between the rail and the driven wheel. The longitudinal forces $H_{L,\mathrm{i}}$ applied to a runway beam may be calculated as follows:

$$H_{L,\mathrm{i}} = \varphi_5 K \frac{1}{n_r}, \tag{5.3}$$

where: n_r – the number of runway beams, K – the drive force according to Ch. 2.7.3. (PN-EN 1991-3 2009), φ_5 – the dynamic factor (see Tab. 2.6. EN 1991-3 2009), i – the integer to identify the runway beam ($i = 1, 2$).

The moment M resulting from the drive force which should be applied at the centre of mass is equilibrated by transverse horizontal forces $H_{T,1}$ and $H_{T,2}$, see Fig. 5.12. The horizontal forces may be calculated as follows:

$$H_{T,1} = \varphi_5 \xi_2 \frac{M}{a}, \tag{5.4}$$

$$H_{T,1} = \varphi_5 \xi_1 \frac{M}{a}, \tag{5.5}$$

where: $\xi_1 = \frac{\Sigma Q_{r,\max}}{\Sigma Q_r}$, $\xi_2 = 1 - \xi_1$, $\Sigma Q_r = \Sigma Q_{r,\max} + \Sigma Q_{r,(\max)}$, $\Sigma Q_{r,\max}$ – see Fig. 5.10, $\Sigma Q_{r,(\max)}$ – see Fig. 5.10., a – the spacing of the guide rollers or the flanged wheels, $M = Kl_s$, $l_s = (\xi_1 - 0{,}5)l$, l – the span of the crane bridge, φ_5 – the dynamic factor (see Tab. 2.6. PN-EN 1991-3 2009), K – the drive force according to Ch. 2.7.3. (PN-EN 1991-3 2009).

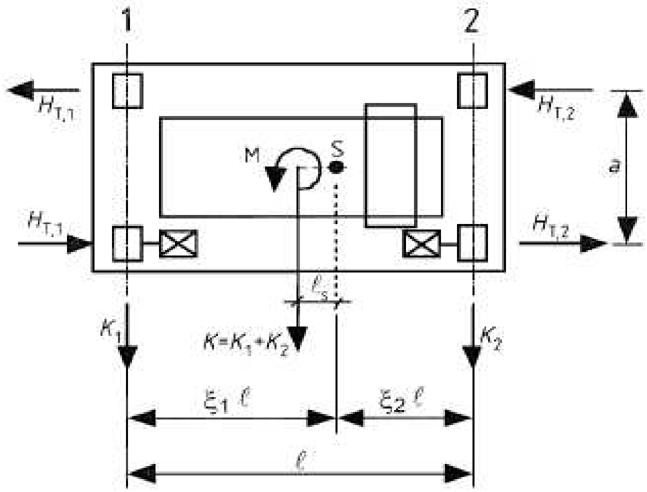


Fig. 5.12. Definition of the transverse forces $H_{T,i}$; 1 – rail i = 1, 2 – rail i = 2 (PN-EN 1991-3 2009)

The drive force *K* on a driven wheel should be taken such that wheel spin is prevented. The drive force K should be obtained from the crane supplier. If the crane supplier will not do it, parameter K can be calculated based on Ch. 2.7.3. (PN-EN 1991-3 2009). It should be noted that the crane drive can be central for a pair of wheels, or separate for each of two wheels.

Horizontal forces $H_{S,i,j,k}$ and the **guide force *S*** are caused by skewing of the crane. The longitudinal and transverse horizontal wheel forces $H_{S,i,j,k}$ and the guide force S can occur at the guidance means of cranes or trolleys while they are travelling or traversing in steady state motion, see Fig. 5.13. These loads are induced by guidance reactions which force the wheel to deviate from their free-rolling natural travelling or transverse direction. The characteristic values of parameters $H_{S,i,j,k}$ and S are given in Ch. 2.7.4. (PN-EN 1991-3 2009).

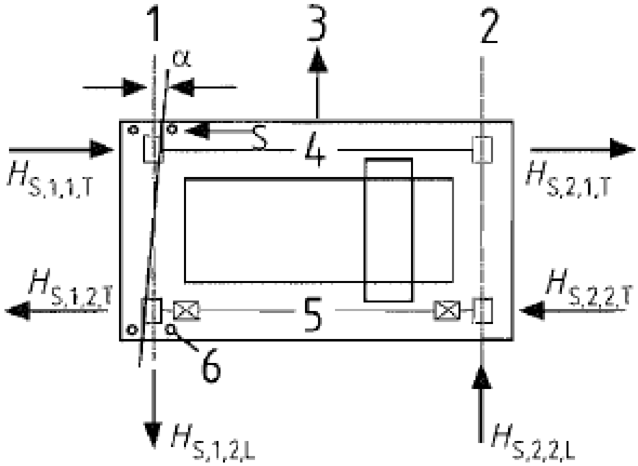


Fig. 5.13. Load arrangement of longitudinal and transverse horizontal wheel forces (with separate guidance means) caused by skewing; 1 – rail i = 1, 2 – rail i = 2, 3 – direction of motion, 4 – wheel pair j = 1, 5 – wheel pair j = 2, 6 – guide means (PN-EN 1991-3 2009)

A separate group of horizontal forces are the special actions. The following can be distinguished:

- buffer forces $\boldsymbol{H_{B,1}}$ related to crane movement, see 2.11.1. (PN-EN 1991-3 2009),
- buffer forces $\boldsymbol{H_{B,2}}$ related to movements of the crab, see 2.11.2 (PN-EN 1991-3 2009),
- horizontal force $\boldsymbol{H_{T,3}}$ caused by acceleration or deceleration of the crab, see 2.7.5. (PN-EN 1991-3 2009).

5.5.3. Dimensioning of RC crane beams

Crane beams are one of the few structural elements, which work not only in bending and shearing, as typical beams, but also in torsion. Occurring in the runway beams torsional moment is the result of work of the crab, of which forces act on the eccentricity of the longitudinal axis of the beam. Therefore, it is necessary to check the structural elements in complex stress states and to add reinforcement for torsion in the form of two-armed closed stirrups and longitudinal bars (Golewski 2012).

Figure 5.14 shows the actual characteristic reinforcement arrangement in the precast RC crane beam of type C. Repository of this reinforcement comprises:

- longitudinal bars in the lower zone of the beam (no. 1) working in tension from loads in the vertical plane,
- longitudinal bars in the corners of the flange of the beam (no. 2) working in tension from the loads in the horizontal plane,
- longitudinal bars in the central zone of the flange (no. 2) working in torsion and as assembly for anchoring four-armed stirrups,
- longitudinal bars in the side zones of the beam in the half its height (no. 2) working in torsion and as anti-shrinkage (for the beam of type C),
- stirrups (no. 3) working in shear and torsion, it should be kept in mind that only the outer arms of stirrups can be considered as working in torsion because their inner arms are outside the effective wall thickness of the torsioned section.
- stirrups (no. 4) working in shear in the beam's flange.

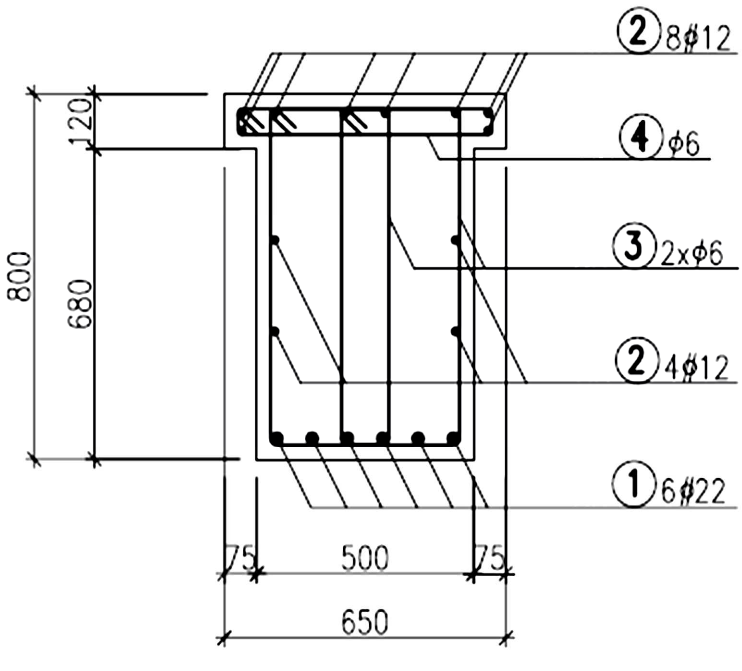


Fig. 5.14. Reinforcement arrangement in the crane beam; explanations of markings in text (dimensions in mm)

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