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Design of nuclear power plants against seismic events —

Part 4: Components

Conception parasismique des installations nucléaires —

Partie 4: Composants

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Foreword

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A list of all parts in the ISO 4917 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

In accordance with IAEA Safety Standards Series No. SSR-2/1, protective measures against seismic events are required, provided earthquakes should be taken into consideration. Earthquakes comprise that group of design basis events that requires taking preventive plant engineering measures against damage and which are relevant with respect to radiological effects on the environment. The basic requirements of these precautionary measures are dealt with in ISO 4917-1.

ISO 4917-4 presents the basis for fulfilling the requirements regarding the verification of the site-specific earthquake safety of components.

Design of nuclear power plants against seismic events —

Part 4:
Components

1 Scope

This document applies to nuclear power plants with water cooled reactors. For other nuclear facilities check the applicability of the document in advance, before it might be applied correspondingly.

This document specifies the requirements for the earthquake safety of components. The operation-specific safety-related requirements for each component, e.g. load-bearing capacity (stability), integrity and functionality (see 4.1) are not the subject of this document. With regard to analysing the mechanical behaviour of the individual components and verifying the fulfillment of their safety related functions, additionally, the respective component-specific standards need to be consulted.

In this document, the term "mechanical components" refers to components such as vessels, heat exchangers, pumps, valves, lifting gear, distribution systems and pipe lines including their support structures in as far as these components are not considered to be civil structures in accordance with ISO 4917-3. Liners, crane runways, platforms and scaffoldings are not considered as being part of these mechanical components.

In this document, the term *electrical components* refers to the combination of electrical devices including all electrical connections and their support structures (e.g. cabinets, frames, consoles, brackets, suspensions or supports).

Supplementary to this document the seismic qualification of electrical components is reported in IEC/IEEE 60980-344.

NOTE This document is independent of national standards. Recommendations, given in Annex A, are mainly based on the Eurocodes-Design-Philosophy and European Standards. Alternatively other equivalent standards or regulations can be used in case the general requirements given in this document together with Annex A can be met.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 4917-1:2024, *Design of nuclear power plants against seismic events— Part 1: Principles*

ISO 4917-3, *Design of nuclear power plants against seismic events — Part 3: Design of structural components*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 4917-1 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
behaviour coefficient
q
reduction coefficient applied to the force magnitude determined by linear analysis of earthquake events

Note 1 to entry: The coefficient, *q*, takes the dissipative effects into account that arise from the materials used, from the support structure and from the structural design.

3.2
centre of gravity
<dynamic> point of action of gravity, which can be considered as the point on the approximated single degree of freedom model of a structure, at which the acceleration is equal to the respective value of the response spectrum

3.3
damping
<modal> damping ratio of the respective eigenmode in mechanical systems

3.4
demand response spectrum
response spectrum that is specified for the design verification or qualification of structures, systems or components and that is usually obtained by multiplying the design response spectrum by safety factors and test-signal specific magnification factors

Note 1 to entry: Demand response spectra may also be created as an enveloping curve of the response spectra at the various places of installation.

3.5
design spectrum
enveloping, widened and smoothed single-degree-of-freedom response spectrum that is used as the basis for the seismic design

Note 1 to entry: In this context, it is differentiated between ground acceleration response spectrum (primary spectrum), building response spectrum (secondary spectrum) and component response spectrum (tertiary spectrum).

3.6
non-linearity
<geometric or physical> nonlinear relationship between the quantities of action and reaction resulting from the equilibrium and kinematic analyses of a system

Note 1 to entry: A physical nonlinearity is the nonlinear relationship between stresses and distortions resulting from a nonlinear material behaviour.

Note 2 to entry: A geometric nonlinearity is defined by a change of dynamic behaviour due to a change of shape, closing or opening of gaps, uplifting or sliding of a component.

3.7
primary system
heavy structure that supports one or more lighter-weight *secondary systems* (3.8)

3.8
secondary system
lighter-weight partial system that is supported by a heavy *primary system* (3.7)

3.9
single-frequency excitation
frequency, which has a time history in which at every point in time only a single excitation frequency (e.g. sine sweep, fixed frequency) occurs

3.10
test response spectrum
response spectrum determined based on the actual motion of the shaking table

3.11
upper limit frequency
frequency above which no significant seismic response in mechanical components would occur

Note 1 to entry: The upper limit frequency may be specified as the cut-off frequency of the excitation spectrum.

4 General requirements

4.1 Basics

The general design requirements for components are specified in ISO 4917-1:2024, 5.1. They include classification of the components, i.e. their assignment to seismic category 1, seismic category 2, or seismic category 3, as well as the general requirements regarding the verification of their earthquake safety.

The design of components and civil structures against seismic events should meet the objectives specified in ISO 4917-1.

It shall be verified for all seismic category 1 components that they are able to fulfill their safety related functions in the case of seismic events. The safety related functions shall be specified for each component. Typical safety related functions are:

a) Load-bearing capacity (stability):

- The load-bearing capacity is the capability of components to withstand the loads to be assumed on account of their strength, stability and secure positioning (e.g. their protection against falling over, against dropping down, against impermissible slipping).
- The load-bearing capacity shall be verified for the component and its support. The building structure interaction loads shall be specified.

b) Integrity:

- Integrity is the ability of a plant component to fulfill its requirements with regard to leak tightness or deformation restrictions.
- The integrity of the components shall be verified based on requirements in accordance with the component-specific standards.

c) Functionality:

- Functionality is the ability of a system or component to fulfill its designated safety functions during and after the seismic event.
- In this context, it shall be differentiated between whether the functionality of the component shall be achieved
  - after the earthquake, or
  - during and after the earthquake.
- Furthermore, it shall be differentiated between active and passive functionalities.
  - An active functionality of a component ensures that the specified movements (relative movements between individual parts) can be performed (closing of clearances, creating or changing of friction forces) and that the electrical functions are maintained.
  - A passive functionality of a component means that permissible deformations and movements are not exceeded. Also, false signals should not appear in electrical equipment.

For all seismic category 2 components it is required to be verified that on account of earthquakes they will not adversely affect the seismic category 1 components and civil structures in a way that these would no longer be able to fulfill their safety related functions. In this context, it is generally sufficient to verify the load-bearing capacity. In certain cases, it may be necessary to verify that limit deformations are not exceeded or that integrity (risk of flooding) is upheld.

Ageing effects that might influence the verification objective shall be taken into account.

NOTE Details regarding ageing effects are dealt with in IAEA Nuclear Energy Series No. NP-T-3.24.

In this document the verifications required for the mechanical and electrical components including their support structures are broken down into individual verification steps, i.e.

1) determining the excitation at the place of installation,

2) modeling and the determination of parameters,

3) analysing the seismic behaviour with respect to the safety requirement,

4) verifying the limit conditions.

These verification steps are dealt with for each of the four possible verification methods, i.e.

i) verification by analysis,

ii) verification by testing,

iii) verification by analogy considerations,

iv) verification by plausibility considerations.

The latter two methods are to be understood as indirect methods according to IAEA SSG-67.

The earthquake safety of a component may be verified on the basis of an individual verification method or on the basis of a combination of various verification methods.

4.2 Verification procedure

The individual procedural steps of the verification procedure are shown in Figure 1.

Depending on the verification objective, individual steps of the verification procedure may be combined, provided, the model is detailed enough. Intermediate results do not need to be determined.

The site excitation parameters to be applied shall be the seismo-engineering parameters of the design basis earthquake in accordance with ISO 4917-1:2024, 5.5, (i.e. ground acceleration response spectrum, reference horizon, directional components, strong motion duration).

The modeling principles in accordance with ISO 4917-1:2024, 6.3.2, shall be applied. Additional requirements dependent on the respective verification methods are specified below in Clause 5 to Clause 8.

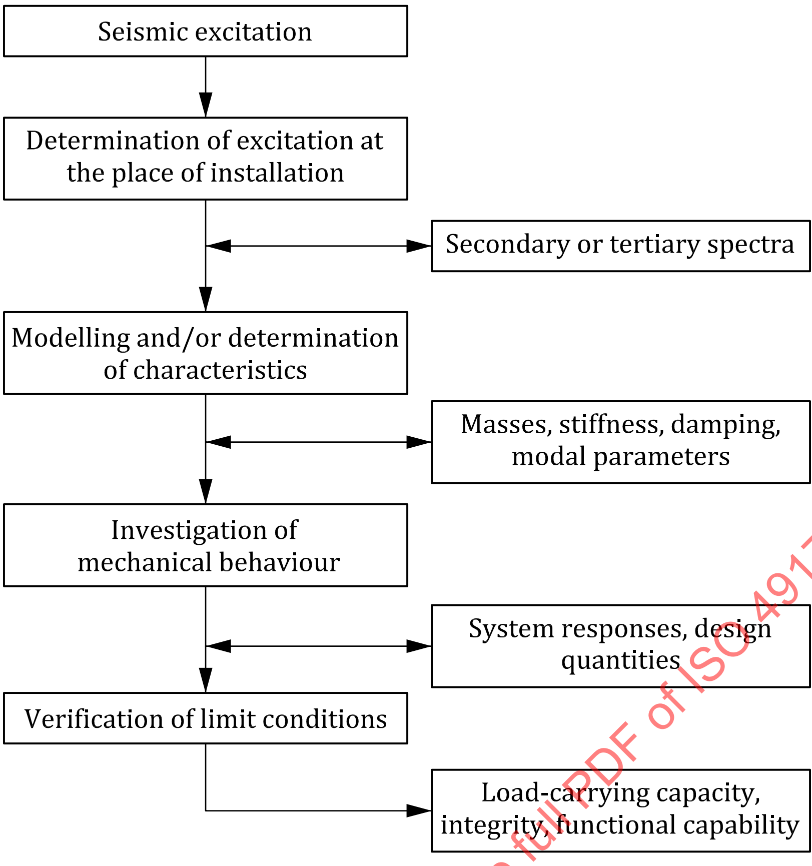


Figure 1 — Procedural steps of the verification procedure

In case of a linear system behaviour, the mechanical behaviour may be analysed separately for the seismic actions and for the other continuous and non-continuous actions. The design quantities shall then be determined by superposition. The effects of seismic actions in each direction and on each single mode may also be determined separately. The design quantity can then be determined by combination of these modal and directional contributions. Superposition shall generally be in accordance with ISO 4917-1:2024, 6.3.1.

In case of a non-linear analysis of the system, all actions having a significant influence on the dynamic behaviour of the component shall be applied with safety margins and combination factors simultaneously.

NOTE Detailed approaches for addressing margins and combination factors can be found in the recommendations in Annex A and in the documents listed in the bibliography.

For the verification of the limit states, the determined design values of the actions are to be compared with the allowable capacities in the appropriate design codes.

4.3 Verification methods

The following verification methods are permissible either individually or in combination with each other:

a) verification by analysis (see Clause 5);

b) verification by testing (see Clause 6);

c) verification by analogy (see Clause 7);

d) verification by plausibility considerations (see Clause 8).

The verification methods to be applied shall be specified for each component regarding its respective task.

NOTE 1 In case of the verification of the functionality of electrotechnical components (e.g. contactors, relays, circuit breakers), preference is given to experimental verification methods.

NOTE 2 Verifications by analogy and by plausibility considerations are in line with IAEA SSG-67 indirect methods.

5 Verification by analysis

5.1 Summary

The basic requirements regarding verification by analysis are specified in ISO 4917-1:2024, 6.3. This concerns the combination of excitation directions, the modeling, the determination and application of the acceleration time histories as well as superordinate aspects of the analysis methods.

The dynamic analysis procedures specified in 5.4.1 shall be applied to the verification by analysis. In well substantiated cases, simplified procedures are permissible.

For pipes or other distributed systems for which design guidelines exist and include seismic load provisions that adequately cover site conditions, it is sufficient that the pipes or distributed system be designed in accordance with those guidelines. Pipes and distributed systems can also be grouped by geometries and material properties, and entire groups can be verified at once using envelope configurations of the existing layouts.

5.2 Excitation at the location of installation

5.2.1 Basics

The excitation at the location of installation shall be determined by one of the following methods:

a) as response time histories of the structural components or building response spectra (secondary responses in accordance with ISO 4917-3);

b) as response time histories or response spectra of the component (tertiary responses as specified in 5.2.3);

c) as artificial time histories which, in accordance with ISO 4917-1:2024, 6.3.3, shall be compatible with the response spectra and the other seismo-engineering parameters of the building structure or component,

d) as response spectra for tertiary responses with the substitution method, see A.1.

Suitable excitations shall be selected for each direction at the place of installation where the response spectra will cover the secondary (or tertiary) design response spectra in the essential frequency range of the component or its substructure. The selection shall be substantiated.

Appropriate load scenarios shall be formed from the selected or the artificial time histories, taking into account the directional assignment, with which the component (or structure with component) is to be excited. The formation of the load scenarios shall be substantiated.

NOTE Details regarding the minimum number of action combinations that are analysed can be found in ISO 4917-1:2024, Clause 6.

Alternatively, the components may be integrated into the model of the superstructure (e.g. building structure) and, thus, may be analysed within the overall model.

Aside from the methods involving time histories or the substitution method for determining the excitation at the place of installation, other mathematical procedures may be applied if they offer equivalent results.

5.2.2 Secondary responses

The responses of the building structure – i.e. the (secondary) response time histories and the (secondary) response spectra – shall be determined within the framework of analysing the structural components in accordance with ISO 4917-3.

The mathematical engineering model provided for the structural components in accordance with ISO 4917-3 shall be expanded by the component as specified in 5.3 if the responses of this component shall be determined directly as a secondary response and not as a tertiary response.

The determined response time histories shall be provided in their digital form and the determined design spectra shall be provided both in their graphical and digital form.

5.2.3 Tertiary responses

The responses of a component supporting a sub-component– i.e. the tertiary response time histories and the tertiary response spectra – shall be determined by applying the secondary response excitations to a suitable mathematical engineering model of the component as specified in 5.3.

If the component behaviour is linear, the generation of tertiary response spectra may be obtained by calculations either in the time or in the frequency domain. Modal superposition methods and modal damping may be used. Alternatively, in the case of sufficiently homogeneous primary systems without any significantly oscillating partial systems, the response spectra (design spectra) for the place of installation of the secondary system may be determined by the substitution method presented in A.1.

The local behaviour of the component at the point of attachement of the sub-component, where tertiary response is generated, shall be adequately represented. Typically, some modes with low participating factors can have large local influence and may not be excluded from the analysis.

If the component behaviour is non-linear, the non-linearity shall be represented in the model. And the tertiary response shall be generated by time integration. The selected damping model shall be substantiated.

The determined response time histories shall be provided in their digital form. The response spectra shall be converted into design spectra as specified in 5.2.4.

For components that have undergone a seismic test qualification, it is permissible to use the results of this qualification to generate tertiary response.

Finally, some envelope qualification codes and standards provide generic tertiary response spectra applicable for the verification of sub-components. If applicable for the site, these generic tertiary response spectra may be used.

5.2.4 Design spectra

Analytically determined tertiary response spectra for the respective place of installation of the sub-components shall be converted to a design spectra in their respective direction that will ensure a robust design of the components, i.e. one that is insensitive to imprecisions of the parameters.

Creating the design spectra from analytically determined response spectra shall comprise the following steps:

a) Evaluation of the imprecisions of the substructure model. If necessary, these imprecisions shall be accounted for within the framework of item e).

b) Averaging the results from the different time history sets.

c) Optional: clipping of spectrum peaks. Only spectrum peaks that are not wider than 15 % of the respective centre frequency should be clipped.

d) Optional: widening spectra. It is recommended to widen the spectra by a value that has been validated after considering uncertainties, e.g. ±10%.

e) Optional: smoothing of the resulting response spectra by applying simplified polygon contours.

NOTE The recommendation under item e) is, generally, met if spectrum valleys with a base width of less than 20 % of the respective centre frequency are surrounded by a plateau originating from the lower peak.

f) Presentation of the response spectra in graphical form for visual inspection (quality assurance) and their provision in digital form for further processing.

The substitution method of A.1 provides the design spectra as immediate result. Therefore, these steps are not applicable to the spectra generated by the substitution method. The spectra generated by the substitution method are directly applicable.

5.3 Modeling

5.3.1 System characteristics

In order to be able to analyse its mechanical behaviour, the component shall be projected onto a suitable mathematical model. This model shall allow describing the essential eigenmodes up to the upper limit frequency of the excitation spectra.

The results of complex models should be checked based on global observations or simplified calculations.

In non-linear models where impacts are induced by the earthquake, the model shall also represent the modes that are excited by such impacts. The corresponding model shall describe adequately the action phases and their consequences.

The stiffness values should preferably be determined on the assumption of a linear-elastic material behaviour. As alternative in well substantiated cases, it is permissible to take advantage of the non-linear material behaviour.

With regard to system behaviour, the non-linearity due to geometry or mechanical design shall be taken into account.

In well substantiated cases, non-linearities may be linearized.

Linearization is allowed if response parameters (loads, displacements, stresses) in the linear model are inside tolerance gap relative to non-linear model response parameters. The recommended value for the tolerance gap is ±10 %.

The mass of the individual component to be applied is the mass corresponding to the analysed operating condition. In accordance with ISO 4917-1:2024, 6.3.2, short-term masses or masses rarely occurring during operation do not need to be applied. Accordingly, the masses from variable loads may be accounted for with ¼ of their actual value unless more detailed requirements have been specified. In the case that the operating conditions during the earthquake case cannot be clearly defined, appropriate bounding cases with respect to the masses shall be analysed.

The damping ratios – in percent of critical damping – needed for verifying the load-bearing capacity and integrity and for determining the tertiary spectra that may be applied should be as listed in column A of Table A.1. In the case of mechanically active components for which the functionality is verified by a deformation analysis, the damping ratios to be applied may be as listed in column B of Table A.1.

Larger damping ratios than the ones listed in Table A.1 may be applied, provided, they are verified.

The degree of utilization under the seismic action combination of the considered structure shall be taken into account when selecting damping values. In areas of low seismicity, the seismic action combination is often not determinant for the design, so that the degree of utilization under this action combination is low. For this case, small damping values should be selected.

In the case of non-linear analyses with hysteresis effects, the viscous damping ratios to be applied should also be as listed in column B of Table A.1.

In analyses where energy dissipation within the material or at the connection and boundary conditions are explicitly considered in the modeling, it shall be ensured that damping is not applied twice by adding an additional equivalent damping in the model.

Factors due to modeling of the components that have an influence on the results of the analysis shall be identified and their influence on the results shall be evaluated.

NOTE Uncertainties on the stiffness and mass modeling of the components are usually already adequately covered by the variation of the excitation coming from the variations of the model of the primary structures (building structure, subsoil).

5.3.2 De-coupling of structures

Structures may be analysed in a de-coupled maner if the interaction between the substructures is taken into account or if neither the oscillation behaviour nor the loads are inadmissibly modified. This is the case if one of the following conditions is met:

a) The relevant design quantities calculated for the de-coupled system shall not be more than 10 % lower than the respective values before its de-coupling. A larger decrease is permissible if special reasons prevail (e.g. low utilization factor).

b) The ratio of component mass, M_{C}, over the mass of the responding part of the structure (e.g. building, floor, shear wall), M_{S}, and the ratio of the main component frequency, F_{C}, over the frequency of the responding part of the structure, F_{S}, meet one of the following criteria (see also ISO 4917-1):

   1) $M_{\mathrm{C}}/M_{\mathrm{S}} < 0{,}01$

   2) $M_{\mathrm{C}}/M_{\mathrm{S}} < 0{,}1$ and $F_{\mathrm{C}}/F_{\mathrm{S}} < 0{,}80$

   3) $M_{\mathrm{C}}/M_{\mathrm{S}} < 0{,}1$ and $F_{\mathrm{C}}/F_{\mathrm{S}} > 1{,}25$

   A larger deviation is permissible if special reasons prevail (e.g. low utilization factor).

If de-coupling is permissible, then in the case of low tuning of the secondary system, its resonating masses can be neglected in the model of the primary system as a first approximation, while in the case of high tuning, they shall be added to the primary system as a first approximation.

Pipe systems may be de-coupled by the method of overlapping. The overlapping pipe region shall cover at least one axial stop and two radial bearings in the two perpendicular directions.

NOTE 2 The method of overlapping is a way of modeling pipe systems where partial systems to be de-coupled are included in the model of the pipe system to be analysed to such an extent that their impact on the pipe system to be analysed is sufficiently accounted for.

In the case of pipe system the secondary pipe lines may be de-coupled if Formula (1) applies:

$$\frac{I_N}{I_H} \leq 0{,}01 \qquad (1)$$

where

I_N is the planar moment of inertia of the secondary pipeline to be de-coupled;

I_H is the planar moment of inertia of the primary system to be analysed.

NOTE 3 The limit value 0,01 mentioned in Formula (1) is a general recommendation, from which deviations are allowed in justified cases and on a national level.

Analysis of de-coupled secondary pipelines should consider the displacements of the primary pipeline. These displacements should be treated as “seismic anchor motion” load.

5.3.3 Fluids

5.3.3.1 Fluids inside components

In the case of components with a variable fluid level, the most unfavorable fluid level existing more than 30 days per annum shall be assumed.

The fluid in a completely filled component may be assumed as being a rigid mass oscillating together with the component.

In the case of partially filled components, the method used may be as follows:

a) Analysis of the load-bearing capacity assuming that the fluid is a rigid mass oscillating together with the component. The sloshing effects of the fluid on the component and built-in components shall be evaluated separately.

b) Application of the method of substitute masses for horizontal oscillations to account for oscillations of the fluid relative to the component (sloshing). In this method, the mass of the fluid may be de-coupled into the “mass at rest” that is rigidly coupled to the component and a “sloshing mass” that can swing freely relative to the component. The damping ratio to be applied for the fluid oscillations should be as listed in Table A.1.

c) Components with geometries for which no simple solutions are available may be projected onto equivalent substitute geometries. In the case of a cylindrical vessel oscillating in the horizontal direction, the fluid mass may be regarded as a rigid pendulum mass.

d) Direct modelling of fluid inside component by appropriate numerical methods (e.g finite element methods or methods from computation fluid dynamics as smoothed particle hydrodynamics).

For the vertical direction of oscillation, the liquid may always be assumed as a rigid mass together with the oscillating component.

Alternative approaches are referenced in A.2.

5.3.3.2 Fluid outside component

The seismic response of a component immersed into a large volume of fluid is affected by

a) the pressure field inside the fluid, which integrated effect on the surface component tend to decrease the seismic excitation, and

b) the fluid displacement around the component, which inertia effect tend to decrease the response frequencies of the component.

NOTE A large volume of fluid means that the inertial coupling between the component and the fluid container can be neglected, the movements of the component does not produce a fluid motion in the vicinity of the container. If this is not the case, see 5.3.3.3.

The fluid outside the component may be represented in the analytical model of the component by

— simple added mass based on the quantity of displaced fluid that can be related to the component immersed section,

— simple added mass and a decrease of the applied excitation due to the pressure field effect, and

— full finite element or computational fluid dynamic CFD representation of the fluid.

5.3.3.3 Fluid between two components

A fluid separating two components might induce a coupling in the seismic response of these two components and significantly affect their response frequencies. The smaller the fluid volume is in comparison to the component immersed surface, the higher is the coupling. If not demonstrated to be negligible, such coupling shall be explicitly accounted for in the analytical model on the components.

The fluid between components may be represented in the analytical model of the component by:

a) Only added mass if the coupling is demonstrated to have low influence on the frequencies. The mass shall then be assessed not only based on the sections of the immersed components but also on the fluid volume between the components.

b) Coupling mass matrices between the degrees of freedom of both components. These matrices then encompass both the inertia and the pressure effect.

c) Finite element or CFD representation of the fluid.

5.4 Analysis of mechanical behaviour and load determination

5.4.1 Analysis methods

In the case of a linear analysis, the mechanical behaviour may be analysed based on one of the following methods:

a) response spectrum method specified in 5.4.2;

b) time history method specified in 5.4.3;

c) quasi-static method specified in 5.4.4.

Other methods may be applied, provided, they produce similar results.

In case of a non-linear system behaviour (see 5.4.5), a non-linear analysis by the time-history method shall be applied unless an adequate and sufficiently accurate linearization is available and well substantiated.

As alternative to the non-linear analysis by the time-history method, non-linear static methods as recommended in A.4 may be applied. This shall be well substantiated.

NOTE In these kinds of analyses, e.g. non-linear statically determined capacity curves are compared to the requirement spectra and are evaluated with respect to the available ductility (capacity spectrum method).

In the case of seismic category 2 components, a quasi-non-linear design with the behaviour coefficient, *q*, as e.g. detailed in A.4 is generally permissible.

Parallel responses of various models shall always be enveloped. Parallel responses from various load conditions may be averaged when performing linear analyses of the component. In the case that non-linear analyses of the component are performed, the results may be conservatively enveloped. Alternatively, the procedure described in ISO 4917-1:2024, A.6. may be used.

5.4.2 Response spectrum method

In the case of components that can be modeled as a system with one degree of freedom, the response spectrum directly produces the maximum response values.

In the case of components that are modeled as a system with more than one degree of freedom, the maximum response values to the individual eigenmodes (e.g. stress resultants, accelerations, deformations) shall be superposed. In this context, the method of the complete quadratic combination (CQC) in accordance with Formula (2) shall be applied:

$$E = \sqrt{\sum_{L=1,K=1}^{M} E_L \times E_K \times \rho_{LK}} \tag{2}$$

For a constant damping ratio, D, the interaction factor, ρ_{LK}, is given by Formula (3):

$$\rho_{LK} = \frac{8 \times D^2 \times (1 + r_{LK}) \times r_{LK}{}^{1,5}}{(1 - r_{LK}{}^2)^2 + 4 \times D^2 \times r_{LK} \times (1 + r_{LK})^2} \tag{3}$$

where

$$r_{LK} = \frac{f_L}{f_K} \tag{4}$$

D	is the damping ratio
E	is the resultant seismic response quantity as the sum of all modal contributions in the respective direction
E_L, E_K	is the modal contribution of the L^{th} or K^{th} eigenmode in the respective direction of the seismic response quantity to be determined
ρ_{LK}	is the interaction factor of the eigenmodes as a function of the modal damping ratios and frequency spacing (frequency ratio, r_{LK}) of the individual eigenfrequencies, f_L and f_K
M	is the number of eigenmodes up to the upper limit frequency
f_L, f_K	is the eigenfrequency of the L^{th} or K^{th} eigenmode

NOTE 1 In case of unequal damping ratios, $D_L \neq D_K$, an expanded Formula (3) is used.

Alternatively, the Gupta or Lindley-Yow methods of combining modal responses can be used.

If all eigenfrequencies are sufficiently widely spaced ($r_{LK} < 0{,}80$ or $r_{LK} > 1{,}20$), the modal contributions may be superposed by the square root of the sum of squares as shown by Formula (5). Different methods of superposition need to be well substantiated.

$$E = \sqrt{\sum_{L=1}^{M} E_L{}^2} \tag{5}$$

NOTE 2 As the space between eigenfrequencies increases ($r_{LK} \ll 1$ or $r_{LK} \gg 1$), Formula (2) becomes identical to Formula (5).

The relative contributions of eigenmodes above the limit frequency shall be adequately taken into account. This means that all eigenmodes up to the upper limit frequency shall be calculated and included in the combination according to Formula (2) or Formula (5). Beyond the upper limit frequency, no frequency contribution may be included in these combinations. Instead, these contributions must be added by a rigid-body contribution. Formula (6) shows this expansion by the rigid-body contribution for Formula (2).

$$E = \sqrt{\sum_{L=1,K=1}^{M} E_L \times E_K \times \rho_{LK} + \left(E_{\mathrm{St}}^0 - \sum_{L=1}^{M} E_L^0\right)^2} \tag{6}$$

where

E_L^0 is the modal contribution of the Lth eigenmode multiplied by the rigid-body acceleration of the seismic response quantity to be determined. Here, the modal contributions are added arithmetically;

E_{St}^0 is the response of a static load case, assuming a rigid-body acceleration in the respective direction.

To account for the rigid-body contribution with a good margin of safety, the expanded Formula (7) or (8) may be applied as expansions of Formula (2) or Formula (5), respectively.

$$E = \sqrt{\sum_{L=1,K=1}^{M} E_L \times E_K \times \rho_{LK} + \left(E_{St}^0\right)^2} \quad (7)$$

$$E = \sqrt{\sum_{L=1}^{M} E_L{}^2 + \left(E_{St}^0\right)^2} \quad (8)$$

In the case of various points of excitation with different response spectra, the multi-support-excitation method may be applied. In this procedure the individual spectra are weighted by corresponding influence functions. Formula (6), (7) or (8) shall be applied to the rigid-body contribution.

ISO 4917-1:2024, 6.3.1 shall be applied to the superposition of the responses from various excitation directions and 5.4.6 to the possible shares from relative displacements.

5.4.3 Time history method

An analysis by the time history method may be performed by a modal time history method or by direct integration. If a modal superposition method is applied, the rigid-body contribution shall be taken into account analogously to the response spectrum method (see 5.4.2).

In accordance with ISO 4917-1:2024, 6.3.3, the applied excitations may be based on those acceleration-response time histories from the analysis of the building structures that cover the design spectrum at the place of installation of the component. Alternatively, artificial acceleration time histories may be applied that, in analogy to ISO 4917-1:2024, 6.3.3, are compatible with the design spectra.

The time increments of the calculation shall not exceed 0,1 times the vibration period of the contributing modes with the highest frequency.

NOTE In case of non-linear calculations with impact or sudden changes of stiffness, the frequency of the highest contributing mode may be significantly higher than the upper limit frequency of the applied excitation.

ISO 4917-1:2024, 6.3.1 shall be applied to the superposition of the responses from various excitation directions and 5.4.6 to the possible shares from relative displacements.

In the case of non-linear calculations, 5.4.5 shall be taken into consideration.

5.4.4 Quasi-static method

The quasi-static method may be used for systems with a homogeneous distribution of stiffness and mass.

Secondary spectra shall be applied to the design of the support structures of secondary systems. The secondary system (supported system) itself shall be designed based on tertiary spectra.

The system responses (stress quantities) may be calculated by a static analysis. In this context, substitute accelerations shall be defined that result in quasi-static actions in proportion to the mass distribution. The substitute accelerations shall be calculated as shown in Formula (9):

$$a_{E,i} = e_i \times S_{a,i} \quad (9)$$

where

$a_{E,i}$ is the substitute acceleration for the direction i

e_i is the factor accounting for the relative contributions of higher eigenmodes for the direction i, (see Table 1 and the next three following paragraphs).

$S_{a,i}$ is the value from the response spectrum for direction i, (see the next two following paragraphes)

The value, $S_{a,i}$, shall be assumed as the largest value of the response spectrum for eigenfrequencies that are larger or equal to the first significant eigenfrequency of the component. If the eigenfrequency is not known, $S_{a,i}$, shall be assumed as the maximum value of the response spectrum. The respective damping and direction shall be taken into account.

In the case of spatially coupled systems – provided, more exacting investigations are not performed – all three values, $S_{a,i}$, shall be set equal to the largest of the three reading values determined.

The values of the factor, e_i, shall be assumed as listed in Table 1. In this context, it shall be well substantiated that an idealization of the component conforming to Table 1 is possible. Other values assumed shall be well substantiated. Lower values may also be applied, provided, their permissibility is verified.

In the case of dynamically stiff components (i.e. the fundamental frequency is higher or equal to the upper limit frequency), the factor, e_i, shall be set equal to 1,0 and the reading value, $S_{a,i}$, shall be assumed as the rigid body acceleration of the spectrum.

Table 1 — Values of factor e_i for Formula (9)

Modeling	e_i
Component with a single response frequency within the frequency excitation range as — Continuous beam with equal span width — Over-hanging beam — Straight beam with any kind of support [a]	1,0
Planar systems (e.g. framework structures, girder grillages, horizontal-plane pipe systems)	1,2
Other systems (with a relevant spatial oscillation behaviour)	1,5

[a] The largest stress resultants (forces, moments) shall be applied at every cross-section.

5.4.5 Non-linear time history analysis

As alternative to the linear analyses specified in 5.4.2, 5.4.3 and 5.4.4, the components may be verified on the basis of a non-linear time history analysis (i.e. the direct integration of the equations of motion). Well substantiated approximation methods are permissible.

The material equations may be approximated by polygonal and, in the simplest cases, by bilinear characteristic curves. The limits of these characteristic curves shall be set by the available limit ductility.

The parameters of the non-linear analysis model shall be evaluated in accordance with ISO 4917-1:2024, 6.3.4, with regard to their range of uncertainty and to the uncertainty of the results. If necessary, sensitivity analyses shall be performed.

The non-linear analyses of the components shall be performed for the selected load conditions specified in 5.2.1.

The time histories of the different excitation directions shall be applied simultaneously and together with all other simultaneously occurring actions.

If the damping ratios are approximated by proportional damping (Rayleigh damping), when selecting the support points it should be taken into consideration that the damping effects remain low enough and, thus, on the safe side.

NOTE For structures with significant rigid-body motion (e.g. due to sliding or in isolated systems), it is necessary to ensure that Rayleigh damping does not artificially damp down the relevant modes to an unrealistically low level.

5.4.6 Relative displacement

In addition to the inertial loads of the components that can be determined, e.g. by response spectra or acceleration time histories, additional loads caused by earthquake-induced displacements at the connection points shall be taken into account if they amount to more than 10 % of the inertial loads (e.g. stress of pipes due to the deformation of long, slim vessels or due to the relative displacement between two parts of a building structure).

The movements or stress quantities resulting from the relative displacements may be superimposed with the inertial loads by applying Formula (10), i.e. by the square root of the sum of the squares.

$$E = \sqrt{E_a^2 + \sum_{k=1}^{n} \sum_{i=1}^{6} (E_{\text{vik}})^2} \quad (10)$$

where

E is the resulting response value from accelerations and relative displacements;

E_a is the resulting response value from all acceleration actions;

E_{vik} is the response value of the statically to be applied i^{th} earthquake-induced displacement component (up to 6 components at each connection point) at the k^{th} connection point (usually one or two, generally, n connection points);

n is the number of connection points.

An alternative approach is described in A.3.

5.5 Verification of the limit conditions

The loads from seismic actions determined in 5.4 (e.g. internal forces, stresses, deformations, accelerations) in combination with other loads shall be compared with the respective capacities. The permissible capacities result from the limit conditions of

a) load-bearing capacity,

b) integrity, and

c) functionality.

Limit states may be defined on a linear or nonlinear basis, via load or displacement quantities (acceleration, velocity, displacement).

A correlation of the design limits of structural engineering and service levels of mechanical engineering is presented in A.5.

The verifications may be carried out by the partial safety concept specified in A.5.2 or by the global safety concept specified in A.5.3. In the case of stability problems, the verification should be carried out as specified in A.5.2.

The verification of action combinations with the design basis earthquakes may only be performed for primary stresses unless deviating requirements are specified below.

NOTE Secondary and peak stresses are specified in component-specific standards.

In the case of components consisting of brittle materials (e.g. cast iron, ceramics) or of unfavorably constructed components (e.g. with fillet welds), the total stress shall be taken into account in addition to the primary stresses. In this context, the secondary stresses and peak stresses shall either be treated as primary stresses or shall, in addition to the primary stresses, be evaluated with regard to their respective failure mode.

With regard to load-carrying capacity (and, if danger of flooding exists, also with regard to integrity), the seismic category 2 components shall be verified in the same way as seismic category 1 components if their loading from seismic actions were determined as specified in A.5 (quasi-nonlinear design).

The analysis of the active and passive functionality shall be performed by verifying the deformation or by the stress analysis.

The deformation verification shall prove that the determined deformations do not adversely affect the required functionality. In this context, it shall be differentiated between:

— Functionality is required only after the earthquake. The verification shall be based on the resulting permanent deformations.

— Functionality is required also during the earthquake. The verification shall be based on the resulting total deformations (elastic plus permanent deformations).

If the verification incorporating a stress analysis is chosen, it shall be based on more stringent limit values as recommended in A.5.

The combination of seismic actions with other actions as well as the design verifications to be performed with these combinations shall be made according to national regulations and appropriate design codes and standards. Recommendations for procedures are given in A.5.2 and A.5.3.

Verification concepts may be defined at national level. Recommendation for an application of the partial safety concept are given in A.5.2, recommendation for an application of the global safety concept are given in A.5.3.

6 Verification by testing

6.1 Verification objective

The verification objective of the test shall be derived from the respective safety related functions.

With respect to the requirements derived from the verification objective for the limit values to be observed, it shall be specified whether these limit values shall be determined during the test.

IEC/IEEE 60980-344 also provides information on this. In 6.2, these are supplemented by detailed specifications.

6.2 Requirements regarding the test object

Testing for the verification of seismic safety may be performed on components (component or individual devices) – hereinafter generally referred to as ‘test objects’ – either in a test bay or in their installed condition in the nuclear power plant.

These experiments shall be performed on original components or, preferably, on design-identical components. Substitute components may be used if they represent the properties of the original components with respect to the respective verification objective.

If the same test object is used for several partial tests, it shall be ensured that the test object continues to have those properties of the original component that are essential to the respective test.

If the experiment is performed in a test bay, the test object shall be mounted in such a way that the original boundary conditions with respect to the verification objective are represented.

The influence of existing vibration isolation systems shall be taken into account. This may be accounted for either in the mounting of the test object or when determining the action quantities.

If a position other than the specified in-plant mounting position of the test object is used in an experiment, the changed influence of gravity shall be taken into consideration.

As far as necessary, connections to neighbouring components shall be taken into account.

If necessary with regard to the verification objective, all operating conditions for the test object that shall be postulated for the seismic event (e.g. pressure, temperature, voltage, electric current, limit values to be observed) shall be determined. If the operating conditions are only partial or not at all accounted for by the experiment, their effects shall be accounted for by some other means (e.g. by analysis).

6.3 Requirements regarding excitation

6.3.1 Basics

The excitation for the verification by testing shall be determined under consideration of the type of excitation as specified in 5.2.

The decisive action for the experiment shall be specified for the respective assumptions (e.g. static substitute loads, response spectrum, time history) as well as for the respective test signal in the excitation directions at the place of installation.

The test object shall be excited at its anchor points in such a way that it receives at least the specified actions. Any deviations shall be well substantiated.

The selected excitation shall, basically, be equivalent to the decisive seismic action. In case of an excitation by means of forced oscillations as specified in 6.3.6, item c), the equivalency shall be verified by comparing the response spectra. Other verification methods, e.g. by the spectral power density, are permissible.

A deviation from the requirement of equivalency between excitation and seismic action is permissible, provided, it is possible to achieve the verification objective by extrapolation (e.g. for stresses in the linear range).

6.3.2 Comparison of actions

A comparison of the actions shall be performed to ensure that the required actions are achieved by the test.

The actions shall be compared based on the response spectra. In the evaluation, the damping of the measured response spectrum shall be larger than or equal to the corresponding value of the required spectrum.

In case of an unknown oscillation behaviour of the test object, it shall be ensured that the demand response spectra are achieved by the entirety of applied test excitations.

If the characteristic frequencies of the test object are known and do not vary due to the excitation, it is sufficient if the individual test signals envelop the demand response spectra in the range of these frequencies. The verification shall be carried out for these characteristic frequencies and, additionally, for frequencies ±10 % away from the characteristic frequencies. The equivalency shall be verified for reliably determined damping values or for the respective damping value to be applied according to column A of Table A.1.

When calculating the test response spectrum, the frequency discretization shall be adjusted to the respective damping ratio to detect if the test response spectrum falls below the required response spectrum.

In the case of damping ratios from 1 % to 5 %, the maximum calculation increments shall be 1/12 of an octave and from 5 % to 10 % 1/6 of an octave. Even higher damping ratios would permit increasing the calculation increments up to 1/3 of an octave.

6.3.3 Excitation axes

The excitations of the test shall be applied simultaneously in all three spatial directions.

A seperation of the sequence of the individual direction-related loads is permissible, provided,

a) the verification objective allows for the superposition of the corresponding reactions of the test object, or

b) it is shown that the behaviour of the test object (eigenfrequencies, stiffness) or that the demand response spectra (frequency ranges with large resonance peaks) are independent of each other with respect to the individual axes, or

c) the multi-axial character of the seismic excitation is taken into account by means of a correspondingly higher test excitation (see 6.5.2).

6.3.4 Transverse motions

In case of a seperation of the sequence of the individual direction-related loads, movements orthogonal to the respective direction or plane of excitation shall be measured.

If transverse motions occur, it shall be ensured that the required value in the direction of excitation is achieved.

6.3.5 Single-frequency test excitations

In case of single-frequency test excitations, the measured amplitude of the excitation frequency in the specified excitation direction shall not fall below 90 % of the corresponding required value.

The level of background noise, d, calculated according to Formula (11), should not exceed 100 % in the range up to five times the highest test frequency.

$$d = \frac{1}{a_n} \times \sqrt{a_{\text{ges}}^2 - a_n^2} \times 100 \tag{11}$$

where

d is the level of background vibration in percent;

a_{ges} is the effective value of the acceleration amplitude within the frequency range to be monitored;

a_n is the effective value of the required acceleration amplitude at the excitation frequency.

NOTE A higher level of background vibration has a conservative effect on the results of stress tests and, therefore, is permissible, provided, this is compatible with the verification objective.

6.3.6 Test excitation methods

The following test excitation methods are permissible taking the restrictions specified in 6.4, 6.5 and 6.6 into account:

a) Static methods:

These include those methods where the values relevant to the verification objective do not change during the test or they change only to such degree that dynamic influences can be neglected (e.g. static deflection tests).

b) Free oscillation methods:

These include those methods where, after application of the initial loads, the system is left to itself with respect to its oscillation (e.g. free vibration decay tests, snap-back tests).

c) Forced oscillation methods:

These include those methods where a time dependent excitation is upheld over the entire duration of the test. In this context, either a single-frequency or a multiple-frequency excitation may be applied.

The single-frequency tests may use, e.g. fixed sine waves, sine sweeps or sine beats as excitation.

The multiple-frequency tests may use, e.g. noise frequencies, spectrum-compatible time histories or the superposition of several individual frequencies as excitation.

6.4 System characteristics and parameters

6.4.1 Static parameters

Static parameters (local and global stiffness) shall normally be determined at the relevant load level. In the case of linear system behaviour, they may be determined for lower load levels. In this context, the static methods as specified in item a) of the first paragraph of 6.3.6, shall be used. The other methods specified under 6.3.6 are also permissible.

6.4.2 Dynamic parameters

Single-axis excitation shall normally be applied for the determination of the dynamic parameters.

The dynamic parameters (e.g. eigenfrequencies, eigenmodes) shall be determined by the methods specified in 6.3.6 item b) or item c) before the stress test.

NOTE When applying the method specified in 6.3.6, item c), dynamic parameters can be determined with a one-axis sine-sweep excitation between 1 m/s^2 and 2 m/s^2 and a sweep velocity smaller or equal to one octave per minute.

The dynamic behaviour shall be examined up to 1,2 times the upper limit frequency.

The damping ratio shall be determined by applying one of the methods specified in 6.3.6, item b) or c). A conservative estimate using the method specified in 6.3.6, item a), (measurement of the static hysteresis) is permissible. In this context, the following restrictions apply:

a) In the case of the methods specified under the 6.3.6, item b), when determining the damping ratio by means of the free vibration test, it shall be considered that the oscillation fade-out, aside from being influenced by system damping, can also be influenced by the dissipation of energy into adjacent systems.

b) With regard to the method specified in 6.3.6, item c) the following applies:

   1) In the case of single-frequency excitation it shall be observed that the excitation lasts long enough for the condition of a steady state oscillation is reached.

   2) In the case of a sine-sweep excitation, the frequency sweep rate applied shall basically not exceed one octave per minute. Higher sweep rates shall be well substantiated.

   3) The damping ratio may be determined from the transfer function at suitable points on the test object. The determination may be based on the half-power bandwidth method or on the resonance amplification according to the following item 4).

   4) A lower limit boundary for the damping ratio, D, of the test object may be calculated by Formula (12):

$$D = \frac{1}{2 \cdot Q} \times 100 \tag{12}$$

where

D is the damping ratio of test object in percent;

Q is the resonance amplification.

NOTE Formula (12) is exactly true only for an oscillator with one degree of freedom. Therefore, Formula (12) applies only if the simplification of the observed system to an oscillator with one degree of freedom is justified.

6.5 Analysis of mechanical behaviour and determination of stress

6.5.1 Methods

The following methods shall be applied when determining the stresses on the test object:

a) Static methods:

If the action quantity is based on an applied deflection force that was determined from the substitute acceleration, $a_{E,i}$, according to Formula (9), then the static methods specified in 6.3.6, item a) shall normally be applied only to systems with a sufficiently homogeneous distribution of mass. In this context, prerequisite for the determination of $a_{E,i}$ is the knowledge or a conservative estimate of the damping ratio of the test object (e.g. values from column A of Table A.1).

b) Free oscillation method:

It shall be ensured that the required acceleration, $a_{E,i}$, according to Formula (9) is applied during at least one cycle of the free oscillations. This method is particularly suited for components with a sufficiently homogeneous distribution of mass.

a) Forced oscillation method:

The stress may be determined by applying the method of forced oscillations as specified in 6.3.6, item c).

6.5.2 Base excitation

6.5.3 General requirements

The excitation of the test object shall basically be measured at the mounting points of the test object. This requirement may be deviated from, provided, the oscillations at the measurement point and at the anchor point are identical with regard to phase and amplitude.

Basically, the damping ratio shall be determined for distinctive low eigenfrequencies. This requirement may deviated from, provided, the values of column A of Table A.1 are applied.

The values of column A of Table A.1 should be applied as damping ratios for higher eigenfrequencies if the damping cannot be accurately determined by experiments (e.g. from the transfer behaviour expressed by a transfer function).

6.5.4 Single-frequency excitation in case of unknown eigenfrequencies of the test object

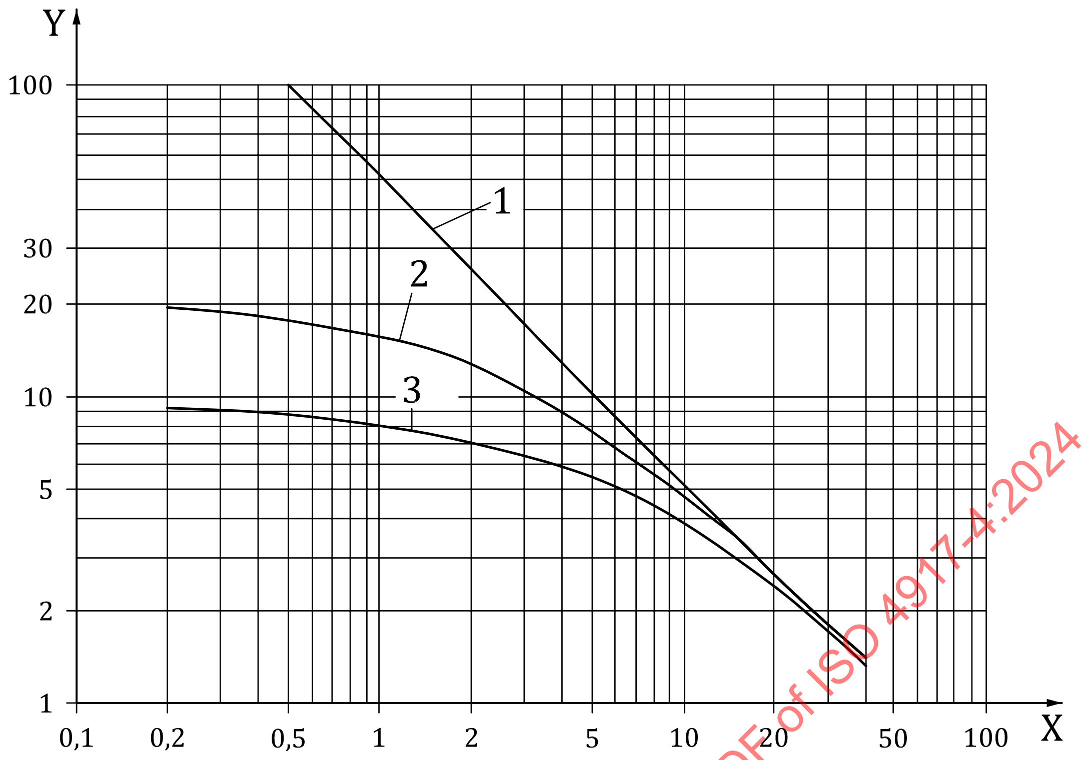
In the case of a single-frequency excitation and unknown eigenfrequencies of the test object, the excitation shall be adjusted such that the test response spectrum envelops the required response spectrum as specified in 6.3.2.

The excitation amplitude of the single-frequency excitation in the direction i, $A_i(f)$, shall be calculated by Formula (13):

$$A_i(f) = k_i \times \frac{a_i(f,D)}{U(f,D)} \tag{13}$$

where

i	is the index for direction x, y, (horizontal) and z (vertical);
f	is the excitation frequency, in Hz;
D	is the damping ration of the test object;
$a_i(f, D)$	is the acceleration of the response spectrum in direction, i;
$U(f, D)$	is the excitation-specific amplification factor as specified in Figure 2 or Figure 3 (depending on the excitation form);
k_i	is the factor for measuring the relative shares of several eigenmodes if only one eigenmode is excited at a time.
	$k_i = 1$, if several eigenmodes are excited simultaneously or if only one eigenmode lies in the test frequency range.
	$k_i = \sqrt{2}$, if only one eigenmode is excited at a time and several characteristic modes lie in the test frequency range.



Key

X damping [5 %]

Y resonance amplification factor

1 sine wave (condition of stable oscillation)

2 sine beat (5 modulated oscillations)

3 sine beat (10 modulated oscillations)

Figure 2 — Resonance amplification factors for a sine wave excitation and for a sine beat excitation at constant frequency

The excitation shall be applied up to the upper limit frequency of the required response spectrum.

An additional test of the rigid-body acceleration shall be performed with at least one period of a freely selected excitation frequency that shall be unequal to an eigenfrequency and smaller than the upper limit frequency, see Formula (14).

$$A_i(f) = k_i \times a_{0i} \tag{14}$$

where $a_{0,i}$ is the rigid-body acceleration (zero-period acceleration) in the direction, *i*.

If time histories of the excitation for the place of installation are available, the excitation may be calculated by Formula (15).

$$A_i(f) = k_i \times r_{\text{eff}} \times a_{0,i} \tag{15}$$

with

$$r_{\text{eff}} = \frac{a_{\text{eff}}(\text{time history excitation})}{a_{\text{eff}}(\text{single frequency excitation})} \leq 1 \tag{16}$$

where r_{eff} is the ratio of the effective values occurring in a time-history excitation and the effective values occurring in a harmonic excitation.

The respective effective value, a_{eff}, shall be determined by Formula (17).

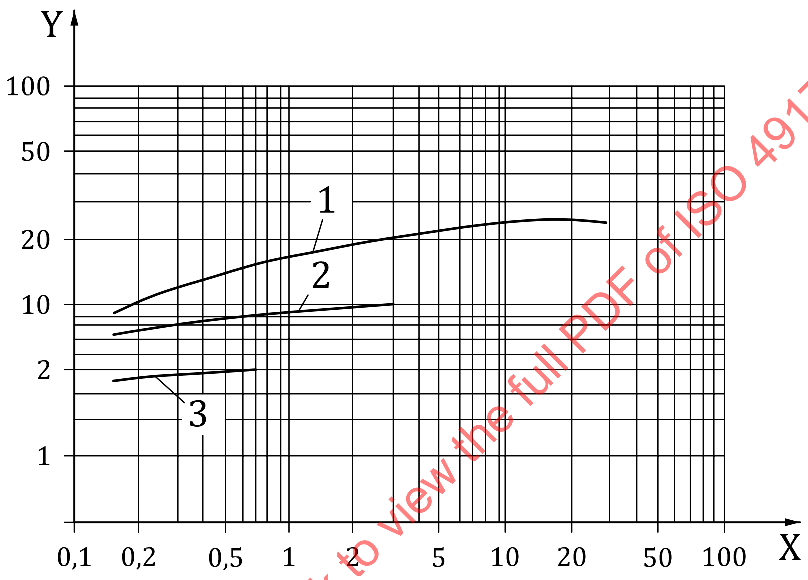
$$a_{eff} = \sqrt{\frac{1}{T} \times \int_{t_0}^{t_0+T} a^2(t)\,dt} \quad (17)$$

where

$a(t)$ is the time-dependent acceleration response function

T is the period length

t_0 is the starting time



Key

X frequency/change in Hz/(oct/min)

Y resonance amplification factor

1 D = 2 %

2 D = 5 %

3 D = 10 %

NOTE Frequency relative to the sweep velocity

Figure 3 — Resonance amplification factors for sine sweep excitation

6.5.5 Single-frequency excitation in case of known eigenfrequencies of the test object

If the eigenfrequencies of the test object are known and lie within the test frequency range, it is sufficient to perform the test at these eigenfrequencies. In this case, the respective test response spectrum at these locations shall reach or exceed the response spectrum.

In the case of test objects with a rigid-body behaviour, it is sufficient to perform the test with a static excitation with the rigid-body acceleration. In case of a dynamic excitation, the rigid-body acceleration may be calculated by Formula (20). The excitation may be performed with a freely selected frequency that is lower than or equal to the upper limit frequency, and it shall be applied for a complete period of the excitation frequency.

Depending on the type of excitation at the place of installation, one of the above mentioned procedures shall be applied to the determination of the acceleration of the response spectrum, $a_i(f,D)$, in the direction i.

6.5.6 Multiple-frequency excitation

In case of specified time histories are available for the earthquake excitation, these time histories may be applied as test input. The validity of the test time histories shall be established by comparing their response spectra with the specified time history specified in 6.3.2.

If more than three specified time histories are available, three representative time histories may be selected as test input signals.

If the test is performed with artificial time histories, with noise signals or with multiple-frequency signals, a complete signal shall be used. In this case, one test run is sufficient. A complete signal is considered to be one that envelops the required response spectrum between the upper and lower frequency limits as specified in 6.3.2.

The artificial time histories shall be generated based on the response spectra at the place of installation of the test object as specified in 6.3.2.

If the test acceleration does not achieve the value of the rigid-body acceleration, an acceleration equal to the rigid-body acceleration shall be applied in an additional test step. This acceleration may be applied statically or dynamically and, independent of the eigenfrequencies, at any frequency less than or equal to the upper frequency limit.

6.5.7 Simultaneity of excitation directions

If the excitation at the place of installation is dominantly two-axial (one horizontal direction, a_h, and the vertical direction, a_v), the test excitation $a_i(f,D)$ and $a_{0,i}$ shall be determined as follows:

a) One-axis test excitation according to Formula (18) and (19):

$$a_i(f,D) = \sqrt{a_\mathrm{h}^2(f,D) + a_\mathrm{v}^2(f,D)} \quad (18)$$

$$a_{0,i} = \sqrt{a_{0,\mathrm{h}}^2 + a_{0,\mathrm{v}}^2} \quad (19)$$

b) Two-axis test excitation or one-axis test excitation, provided, the requirements according to 6.3.3 item b) (de-coupled axes) are met according to Formula (20) and (21):

$$a_i(f,D) = a_{\mathrm{h,v}}(f,D) \quad (20)$$

$$a_{0,i} = a_{0,\mathrm{h,v}} \quad (21)$$

where

$a_i(f,D)$	is the spectral value of acceleration in direction, i;
$a_{0,i}$	is the rigid-body acceleration (zero period acceleration) in direction, i;
a_h	is the horizontal acceleration;
a_v	is the vertical acceleration.

If the excitation at the place of installation is three-axial, the test excitation $a_i(f,D)$ and $a_{0,i}$ shall be determined as follows:

a) One-axis test excitation according to Formula (22) and (23):

$$a_i(f,D) = \sqrt{a_x^2(f,D) + a_y^2(f,D) + a_z^2(f,D)} \quad (22)$$

$$a_{0,i} = \sqrt{a_{0,x}^2 + a_{0,y}^2 + a_{0,z}^2} \tag{23}$$

b) Two-axis test excitation (vertical and horizontal):

i) vertical according to Formula (24) and (25):

$$a_i(f,D) = a_z(f,D) \tag{24}$$

$$a_{0,i} = a_{0,z} \tag{25}$$

ii) Horizontal according to Formula (26) and (27):

$$a_i(f,D) = \sqrt{a_x^2(f,D) + a_y^2(f,D)} \tag{26}$$

$$a_{0i} = \sqrt{a_{0x}^2 + a_{0y}^2} \tag{27}$$

c) Three-axis test excitation or one- or two-axis test excitation, provided, the requirements according to 6.3.3 item b) (de-coupled axes) are met according to Formula (28) and (29):

$$a_i(f,D) = a_{x,y,z}(f,D) \tag{28}$$

$$a_{0,i} = a_{0,x,y,z} \tag{29}$$

6.5.8 Centre-of-gravity excitation

The excitation at the centre of gravity (e.g. in the installed condition in the plant) may only be applied in the case of components with a homogeneous distribution of mass.

It shall be ensured that the required substitute accelerations, $a_{E,i}$, according to Formula (9) are applied,

With regard to the test excitation requirements (e.g. test frequencies or test frequency range), the same requirements apply as those specified for the base excitation (see 6.5.2).

6.6 Verification of limit conditions

The experiment-based load analysis shall verify that the test objects fulfil their safety related functions as specified in 4.1. In this context, the loads specified in 6.5 shall be determined.

For the verification of permissibility of the loads, the test excitation methods specified in 6.3.6 may be applied, with the following restrictions:

a) With respect to functionality, the method specified in 6.3.6, item a) may only be applied in the case of a deformation-related failure.

b) With respect to functionality under load, the method specified in 6.3.6, item b) may only be applied if the free vibration decay time is longer than the length of the required interval for a safety-related functioning of the test object. In this context, the amplitude decrease shall also be taken into consideration.

The following methods, among others, are permissible for the verification of safety against failure:

— To verify the load-bearing capacity and the integrity, the proof that the limit conditions specified under 5.5 are not exceeded may be performed by stress or strain measurements on significant force-transmitting parts of the test objects.

— To verify the functionality, checks may be performed regarding possibly occurring deformations to ensure that no impermissible condition occurs under load.

— If no stresses or deformations are found, it is permissible to increase the test load by a safety factor, γ_F. The safety factor, γ_F, shall be calculated as specified by Formula (30):

$$\gamma_F = \gamma_{F1} \times \gamma_{F2} \quad (30)$$

where

γ_{F1} is the safety factor against failure, γ_{F1} = 1,1;

γ_{F2} is the safety factor for the number of test objects between 3 and 1 (transfer factor, $1{,}0 \le \gamma_{F2} \le 1{,}4$)

In well substantiated cases the safety factor γ_{F2} may be reduced. If it can be proven with respect to the verification objective that the most unfavourable test object has been chosen, a safety factor γ_{F2}= 1,0 may be used.

If a verification of safety against failure is possible with the safety factor γ_F specified in Formula (30), the verification objective is considered as having been achieved, provided,

i) a limit load test leads to at least a safety factor γ_F, or

ii) a test is carried out with loads increased by the safety factor γ_F and the verification objective is achieved, or

iii) a test with the safety factor γ_F = 1,0 verifies a safety margin for the stresses or deformations, or

iv) an extrapolation of a test load condition lower than the specified earthquake load condition verifies compliance with the safety against failure as specified above.

Provided, the verification of load-bearing capacity, integrity or functionality is not required to comply with certain mechanical stress or strain limits, then the completed test is considered as proof of permissibility.

6.7 Combination of several verification steps

When combining several verification steps in one test step, the requirements for the contained partial steps need to be considered only to the extent as necessary for the respective verification objectives. Only the respective test objective needs to be verified.

6.8 Documentation

The documentation shall normally include the following information:

a) Regarding the test object:

— identification marking of the test object,

— identification of the test object (e.g. type, manufacturer, technical drawing),

— data sheet (e.g. information on materials, certifications),

— verification objective.

b) Regarding the layout of the test:

— description of the equipment for testing, measuring and data collection,

— test conditions,

— diagram of measuring points.

a) Regarding the implementation of the test:

— date of implementation of the test,

— test laboratory, tester,

— type of excitation signal,

— excitation amplitude,

— frequency range,

— direction of excitation,

— specific observations.

7 Verification by analogy

A verification by analogy shall be based on the following reference results:

a) the results from analysis or experimental verifications as specified in Clause 5 or 6 that were performed on similar, type-identical components,

b) the quantitatively documented results for the respective component regarding its behaviour under other actions, provided, these results are suited to make comparisons.

The available reference results shall be evaluated regarding transferability of the actions and resistances, and it shall be quantitatively substantiated that this procedure verifies that the respective component can fulfill its safety related functions.

Static system characteristics (global or local stiffness) and parameters (material properties) may be used as reference results, provided, the mechanical design and materials are qualitatively similar. This also applies to a non-linear behaviour which shall be comparable at the respective stress levels.

The dynamic system characteristics (e.g. eigenfrequencies, eigenmodes) may be used as reference if the static system characteristics are comparable and any changes with respect to mass distribution are evaluated.

Higher values for the damping ratios than the ones specified under Clause 5 may be applied, provided, they are well substantiated for the specific case of application.

If, in limited frequency ranges, the reference excitation is smaller than the required excitation, it shall be verified that this is either negligible for the specific component or that this is covered by the higher excitation level when verifying the limit conditions.

8 Verification by plausibility considerations

A verification by plausibility considerations shall be based on factual experience as follows:

a) Experience regarding the behaviour of similar, type-identical components in nuclear or non-nuclear facilities during earthquakes that have actually occurred.

b) Experience from earthquake verifications for similar, type-identical components that enable an evaluation of the design planning or mechanical design of other components regarding earthquake safety.

The factual experience shall be evaluated regarding transferability of the actions and resistances. On this basis it shall be substantiated in writing that it is plausible that the respective component will be able to fulfill its safety related functions.

To gain factual experience as specified above under item a), and for evaluating the mechanical design as specified above under item b), it is necessary

— to peruse the design documents, and

— to perform walkdown inspections of the plant.

The observations made in this context shall be documented in writing.

Walkdown inspections should normally be performed according to the schematic sequence shown in Figure 4.

Walkdown inspections should be performed in the real power plant. If a computer aided design (CAD) model is available, they can also be performed as a virtual walkdown. Prerequisite in the latter context is that the CAD model and all data relevant to the evaluation are current and quality assured.

The evaluation and application of the walkdown inspection results shall be well substantiated. The substantiating criteria shall be based on the requirements that shall be met (i.e. load-bearing capacity, integrity, functionality).

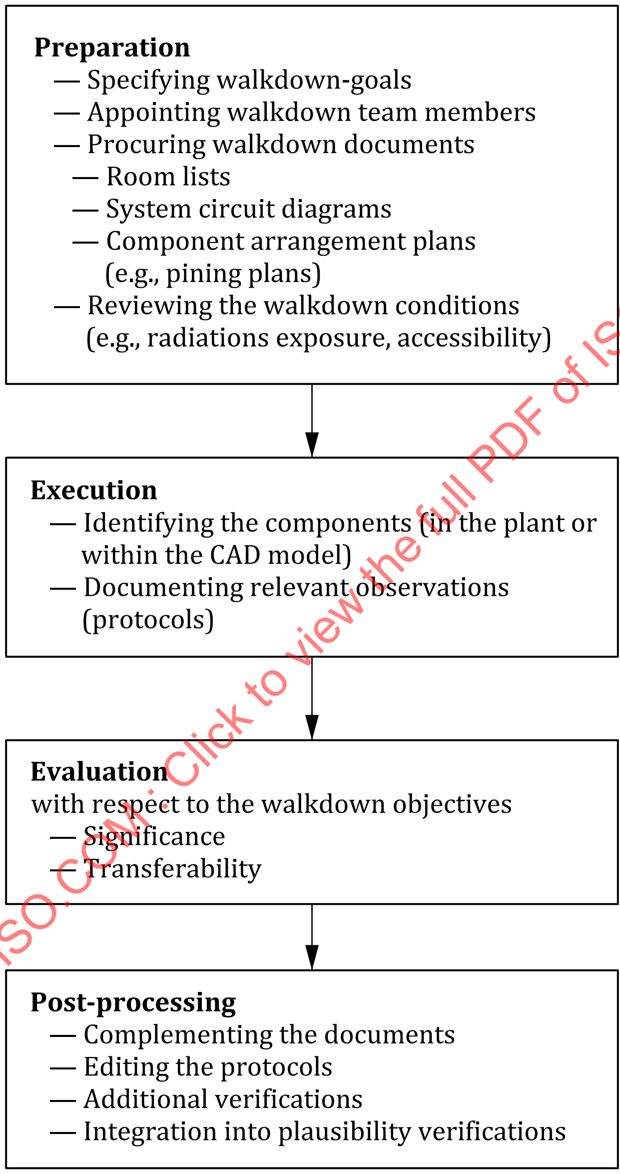


Figure 4 — Schematic sequence of walkdown inspections

Annex A
(informative)

Recommendations with comments

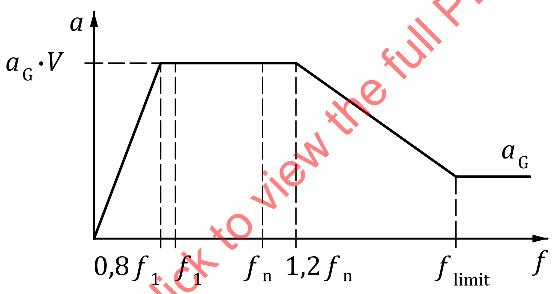
A.1 Recommendation to 5.2.3

In the case of sufficiently homogeneous primary systems without any significantly oscillating partial systems, the response spectra (design spectra) for the place of installation of the secondary system may be determined by the substitution method presented below.

NOTE 1 The primary system is the component or it is the building with the component, and the secondary system is the built-in part of the component.

NOTE 2 A oscialating secondary system is a subsystem that is tuned to the dominant eigenfrequency of the primary system and, therefore, has the tendency to produce resonance-type vibration responses in this frequency range.

The shape of the response spectrum should be determined as shown in Figure A.1. The spectrum amplification factor with respect to the acceleration of the primary system at the place of installation of the secondary system (here: the acceleration of the component) should be determined as shown in Figure A.2.



Key

f frequency (the X-axis should be logarithmic);

f_1 lowest decisive eigenfrequency of the primary system at the lower limit value in the variation range of the system parameters, however, not higher than the rightmost corner frequency of the highest plateau of the associated response spectrum;

f_n highest decisive eigenfrequency of the primary system for the upper limit value in the variation range of the component parameters, however, not higher than the rightmost corner frequency of the highest plateau of the associated response spectrum;

f_{lim} upper limit frequency of the response spectrum of the primary system;

a acceleration;

a_G acceleration of the primary system (component) at the place of installation of the secondary system (built-in part);

V spectra amplification factor as shown in Figure A.2.

Figure A.1 — Determination of the shape of the response spectrum