Transactions, **SMiRT-24**
BEXCO, Busan, Korea - August 20-25, 2017
Division VI

SEISMIC DESIGN AND QUALIFICATION OF FASTENINGS IN NUCLEAR POWER PLANTS RELATING TO EUROPEAN REQUIREMENTS

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ABSTRACT

For any nuclear power plant design basis accidents such as earthquakes have to be considered in view of necessary plant engineering measures. These measures require safety-related components and building structures with a safety-orientated seismic design, as well as safety-related fastenings, which are necessary for the anchoring of components or structural members in concrete.

Safety-relevant fastenings are subdivided into two groups: cast-in fastenings (anchor plates with headed studs or screw connections and anchor channels) and post-installed metal anchors (expansion anchors, undercut anchors and bonded anchors). The application of these fastenings requires adequate seismic qualification and seismic design.

For the seismic design as a deterministic design the knowledge of the whole usual calculation procedure – starting with the specification of the actions due to the design basis earthquake up to the determination of the action effects at the fastening locations – is of vital importance to guarantee a well-balanced safety concept. This calculation procedure illustrates the different conservative assumptions of the resulting action effects at the fastening locations. So in contrast to fastenings of conventional buildings, uncertainties caused by the analytical model for the determination of the fastening action effects are of minor importance.

In addition to the design also the qualification of safety-related fastenings in nuclear power plants require the consideration of the nuclear specific seismic aspects. Adequate demands on the design and qualification of those fastenings are different to the demands for seismic qualified fastenings of conventional buildings.

INTRODUCTION

Earthquakes belong to that group of design basis accidents that requires preventive plant engineering measures against damage (IAEA requirements). The basic requirements of these preventive measures including the seismic design requirements are dealt with nuclear safety standards such as the German KTA-standards KTA 2201.1 (2011) and KTA 2201.3 (2012) or the Finish YVL-guide YVL B.2 (2011). These standards specify the demands on the determination of the design basis earthquake as well as the demands on seismic analysis and design of safety related building structures and components.

In view of the seismic design of safety related building structures and components, you also have to take care of the seismic design of safety-related anchoring of components and structural members in concrete. Those safety related fastenings are to be qualified for specified seismic action effects, especially for seismic induced large crack openings. Qualification and design demands are provided in European guidelines, which correspond to the safety concept of the Eurocodes. In addition the seismic design requirements of the nuclear safety standards need to be considered.

SEISMIC QUALIFIED FASTENINGS IN NUCLEAR POWER PLANTS

Fastening Systems

The necessary precaution of nuclear power plants against damage requires the observation of the protection goals such as

- controlling reactivity,
- cooling of fuel assemblies,
- confining radioactive substances and
- limiting radioactive exposure.

The components and building structures required for compliance with these protective goals are defined as safety-related components and building structures (including structural members as parts of building structures). Consequently safety-related fastenings are fastenings of components and structural members, which are safety-related in themselves or whose failure could affect safety-related components or structural members. All safety-related components and building structures as well as safety related fastenings require a seismic design considering the design basis earthquake (DBE) or safe shutdown earthquake (SSE), as described in the subsequent chapter.

Safety-related fastenings qualified for seismic action effects can be subdivided into the following groups (see Fig. 1):

- cast-in fastenings: headed studs, anchor bolts as screw connections and anchor channels (with rigid connection between anchor and channel),
- post-installed fastenings: metal anchors like expansion anchors, undercut anchors and bonded undercut anchors.

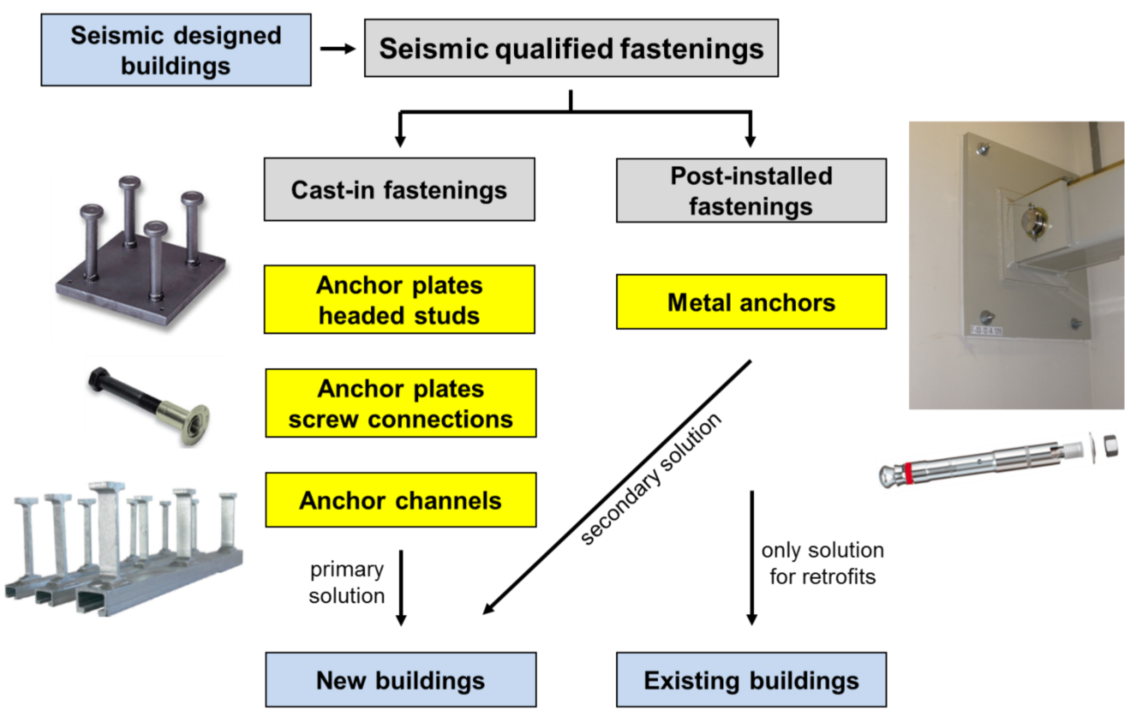

Figure 1. Different types of seismic qualified fastenings

Figure 2. Exemplary applications of fastenings in nuclear power plants

Cast-in fastenings are provided for new buildings. They are built in along with the reinforcement, before pouring concrete. In comparison to post-installed fastenings, cast-in fastenings shall be preferred for dynamic action effects as those due to seismic actions.

Metal anchors as post-installed fastenings represent the only solution for retrofits in existing buildings. They are sensitive to concrete cracks resulting from the seismic action effects with cyclic loading characteristics. These relative large cracks can reduce the load bearing capacity of the metal anchors and result in considerable deformations. So according to the DIBt-Guideline (2010), for the assumption of a rigid anchorage the displacement in all directions should not exceed 3 mm for an individual anchor.

Application range

Typical applications of fastenings in nuclear power plants are shown in Fig. 2. As mentioned before, for the erection phase cast-in fastenings should be applied as primary solution. They represent rigid connections which are appropriated for seismic actions and they can be designed advantageously regarding further requirements resulting from the building and equipment configuration. So anchoring with cast-in-fastenings is the more cost-efficient solution in comparison to anchoring with metal anchors (possible exception: metal anchors with small diameter for small anchor loads).

Anchor plates with headed studs or screw connections are qualified for high loads. So large piping systems with their attachments designed as rigid connections represent the essential application range of these fastenings.

As a supplementary solution to anchor plates anchor channels can be applied for small and moderate seismic loads. This cost-effective solution is characterized by high flexibility for redesign or new attachments during the lifetime of the nuclear power plant. Typical applications are the attachments of cable trays as shown in Fig. 2.

In view of the application of the different fastening alternatives, for seismic load bearing it is necessary to specify an anchoring concept at an early stage of the detailed design process. Such a concept has to fulfil the demands on safety and economic as well as the demands on modification measures during the design phase and during the operation phase as a result of the periodical safety reviews and the assessment of nuclear specific accidents (e.g. Fukushima accident). So the anchoring concept is a part of the necessary ageing managing concept considering highly flexibility and sufficient load margins.

SEISMIC DESIGN OF BUIDLING STRUCTURES AND COMPONENTS

Seismic actions

The effects of (tectonic) earthquakes manifest themselves in considerable amounts of energy being released, due to the rock strata shifting. From the hypocenter, shock waves spread out at different speeds and amplitudes. The earthquakes themselves which trigger these waves can be defined and quantified either by their magnitude or intensity (see Figure 3). Magnitude measures the energy released to the hypocenter of the earthquake underground. Intensity is a measure of the impact of seismic waves and dislocations at the surface of the earth on people, objects and building structures.

Based on all relevant magnitude-orientated and intensity-orientated data a site specific seismological expertise determines the site specific design basis earthquake (DBE) or so-called safe shutdown earthquake (SSE). The design basis earthquake shall be specified by evaluating deterministic seismic hazard assessment (DSHA) as well as probabilistic seismic hazard assessment (PSHA). According to the German KTA rule KTA 2201.1 (2011) DSHA and PSHA result in the site specific intensity with the corresponding ground acceleration response spectrum and the corresponding rigid-body accelerations (PGA: peak ground acceleration). Such a response spectrum represents the maximum acceleration amplitudes of a damped single-degree-of freedom oscillator with various eigenfrequencies and a constant damping ratio in response to a non-stationary excitation.

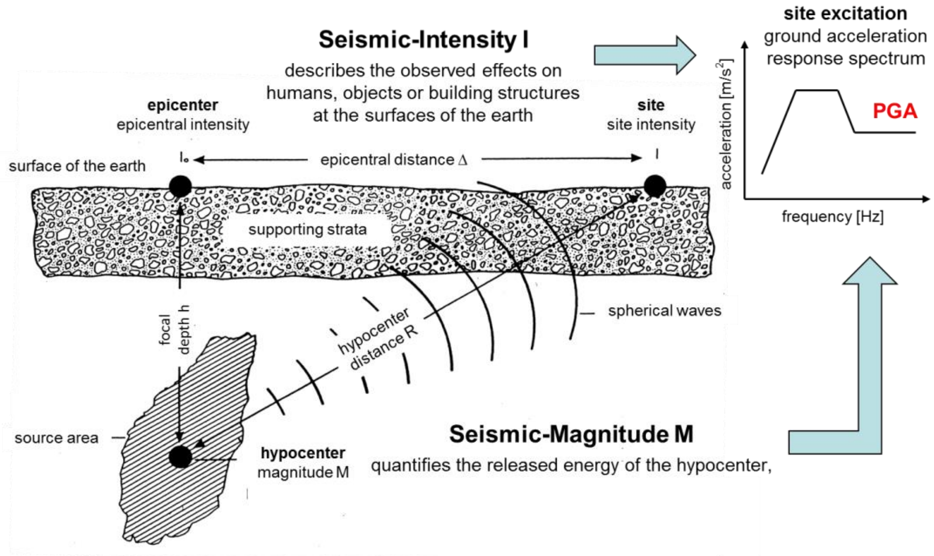

Figure 3. Specification of seismic actions(Design Basis Earthquake (DBE/SSE))

Fundamental design requirements

Regarding the necessity of a seismic design, the components and building structures can be subdivided into three classes (according to KTA 2201.1 (2011) or YVL B.2 (2011)):

- **Class I:** Components and building structures that are required to fulfil the protective goals. They form the group of safety-related components and building structures.
- **Class IIa:** Components and building structures that do not belong to Class I and which, due to their own damage and the sequential effects possibly caused by an earthquake, could detrimentally affect the safety related functions of Class I components and building structures.
- **Class IIb:** All other components and building structures.

Depending on these classes different verification demands are formulated. So with regard to design basis earthquake, seismic design is necessary for components and building structures of Class I and Class IIa as well as all safety related fastenings.

Based on the European approach, such a seismic design requires the consideration of the partial safety concept of EN 1990 (2010) in combination with nuclear specific requirements (see Figure 4). For example, these requirements are specified in DIN 25449 (2015) or in KTA 2201.3 (2012). According to DIN 25449 (2015) three different requirement categories are defined for the resistance part: A1 for design situations during normal operation, A2 for accidental design situations regarding extraordinary actions according to EN 1990 (2010) or EN 1998-1 (2010) and A3 for accidental actions with a minor probability of occurrence (occurrence rate: $\leq 10^{-4}$ / year) like those due to DBE.

It shall be noticed, that also fastenings will be designed according to European standards based on the partial safety concept of EN 1990 (2010). So fastening design of conventional buildings is regulated in FprEN 1992-4 (2016), including the design for seismic actions according to EN 1998-1 (2010). For the seismic design of fastenings of nuclear buildings the German DIBt-Guideline (2010) for mechanical anchors can be taken as a basis. This guideline also considers the DBE with the requirement category A3.

$$\boxed{E_d = E(\gamma_F \cdot F_k) \;\leq\; R_d = R_k / \gamma_M}$$

partial safety factors: γ_F: action effects E / actions F

γ_M: material /structural resistance R

$\gamma_M = \gamma_M$(A1/A2/A3)

DBE (SSE): $\gamma_M = \gamma_M$(A3)

$$\left.\begin{array}{l}\text{permanent and temporary design situation}\\ \gamma_G \cdot G_k + \gamma_P \cdot P_k + \gamma_{Q,1} \cdot Q_{k1} + \Sigma(\gamma_{Q,i} \cdot \psi_{0,i} \cdot Q_{ki})\end{array}\right\} \gamma_M(\text{A1})$$

$$\left.\begin{array}{l}\text{accidental design situation}\\ G_k + P_k + A_d + \psi_{1,1} \cdot Q_{k1} + \Sigma(\psi_{2,i} \cdot Q_{ki})\\ \text{seismic action effects}\\ G_k + P_k + A_{Ed} + \Sigma(\psi_{2,i} \cdot Q_{ki})\end{array}\right\} \gamma_M(\text{A2/A3})$$

actions G, P, Q_k		partial safety factor $\gamma_G, \gamma_Q, \gamma_P$	combination factor		
			ψ_0	ψ_1	ψ_2
G	dead load	1.35 / 1.00	-	-	-
P	prestressing	1.00	-	-	-
Q	variable imposed loads	1.50	0.5 – 1.0	0.2 – 1.0	0 – 1.0

Figure 4. Partial safety concept according to DIN 25449 and EN 1990

Seismic structural analysis

For the seismic verification of fastenings with regard to a deterministic approach a calculation procedure is carried out, which starts with the actions due to the design basis earthquake and ends with the determination of the action effects at the fastening locations. Dynamic analysis of the total structure including the buildings structure and the components with their attachments would be realistically and the results of these analyses would also consider nonlinear effects like plastic deformations. Because these analyses are too sophisticated, generally the total structure will be subdivided in manageable partial structures or substructures with different calculation steps as shown in Fig. 5a and 5b.

For the dynamic analyses of the different partial structures the responses spectrum method can be used advantageously, starting with the ground response spectra of the design basis earthquake (primary spectrum). As a result building response spectra at different building locations (secondary spectra) will be obtained as well as further spectra for component and component-substructures (tertiary spectra …). So the action effects of the different fastening points can be determined.

Regarding this calculation procedure different conservative aspects are evident. Some of these aspects, which are illustrated in KTA-GS-80 (2013) in detail, are mentioned in the following:

- For the influence of the interaction between building structure and subsoil (soil–structure interaction) the soil characteristics will be varied in a reasonable range represented by lower, medium and upper soil stiffness, and after then the analytical results with different soil stiffness’s will be enveloped.
- Due to widening and smoothing of the calculated spectra the excitations are overestimated.
- Response spectrum method considers maximum structural responses.

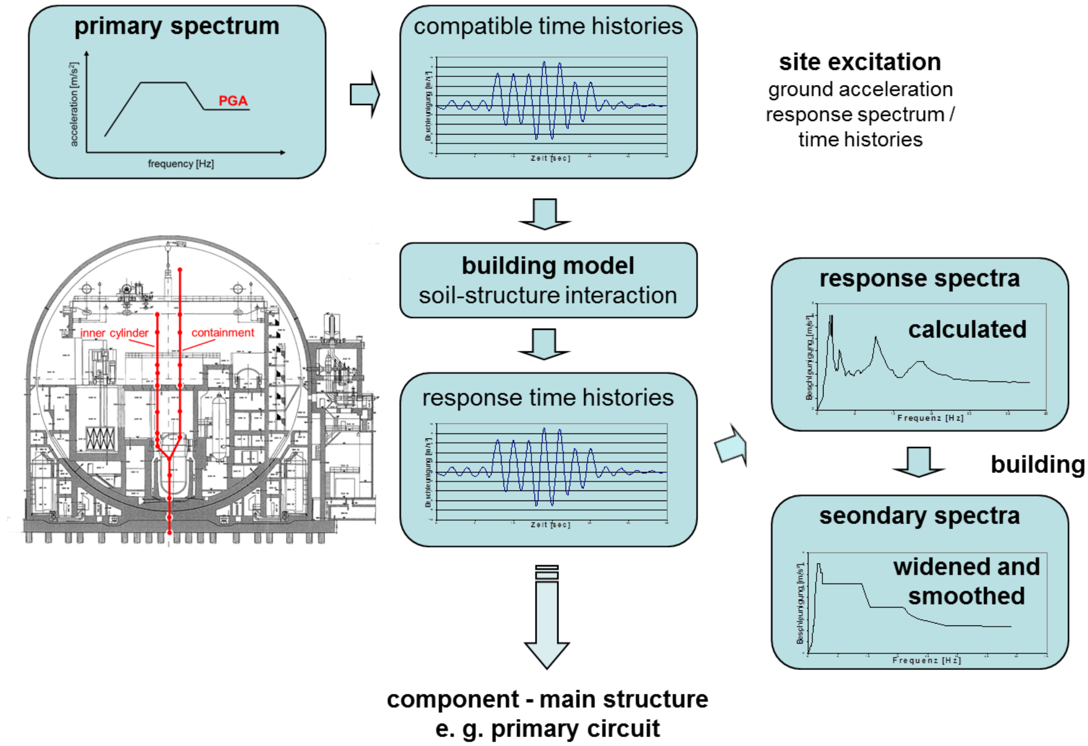

Figure 5a. Seismic calculation procedure: building structure

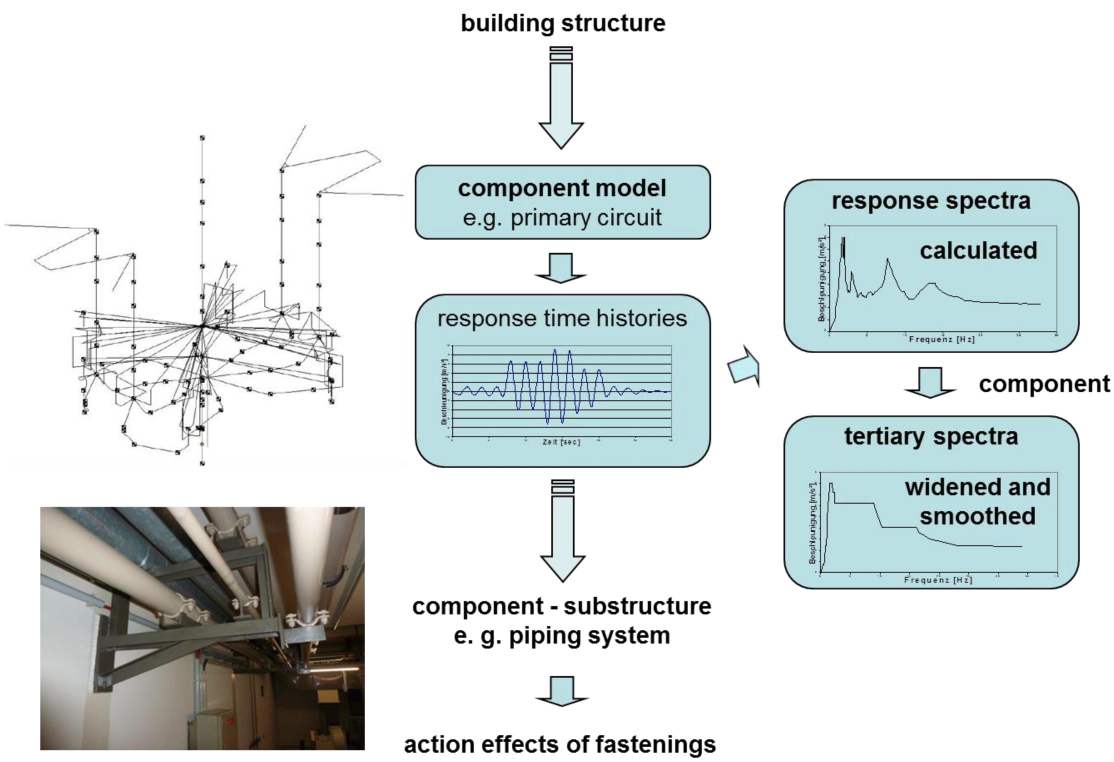

Figure 5b. Seismic calculation procedure: components and their fastenings.

SEISMIC DESIGN AND QUALIFICATION OF FASTENINGS

General remarks

For the assurance of the seismic load transfer from the attachment into the reinforced concrete an adequate design is necessary which considers all design relevant aspects:

- Application of safety relevant fastenings, qualified for seismic action effects, including the seismic resistance values, and supervised during installation,
- Sufficient knowledge about the action effects of the fastenings to avoid uncertainties (see Fig. 5a and b),
- Adequate design concept or verification procedure with regard to an accepted safety concept of nuclear power plants (e.g. defence in depth which demands on the consideration of design basis accidents like DBE with an occurrence rate of $\leq 10^{-4}$ / year).

For the compliance of these seismic design and qualification demands different European standards are available, but for the relevant fastenings like metal anchors, headed studs and anchor channels they are inadequately. For the seismic design of these fastenings in ordinary buildings FprEN 1992-4 (2016) can be applied, but with regard to the approval only ETAG 001 Annex E (2013) (nowadays replaced by TR 049 (2016)) with reference to metal anchors is available. Metal anchors are also in the focus of the German DIBt-Guideline (2010). Based on DIN 25449 (2015) the DIBt-Guideline (2010) provides the design and qualification demands for metal anchors applicable in nuclear power plants.

So only for metal anchors a well-known approach is available – for ordinary buildings as well as for nuclear power plants. The seismic qualification of the other fastening types requires additional expert reports as shown in Fig. 6: expert reports in addition to ETAG 001 Annex E (2013) or TR 049 (2016) for ordinary buildings or expert reports in addition the DIBt-Guideline (2010).

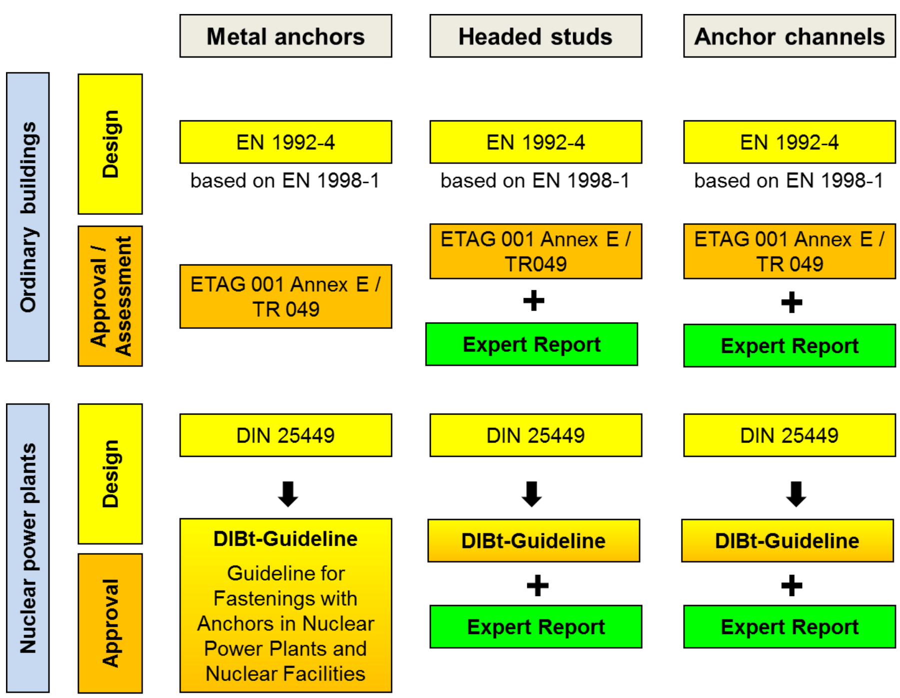

Figure 6. Design and approval for seismic qualified fastenings.

Eurocode 2-4 and ETAG 001 Annex E

The European standard FprEN 1992-4 (2016) also referred to Eurocode 2-4 deals with the fastening design of ordinary buildings. The verifications for seismic loadings are linked together with EN 1998-1 (2010). So the demands on the specification of seismic actions and on verification analysis are on a lower level than those for nuclear power plants. Furthermore different possible fastening types are permitted. All these aspects result in a lack of knowledge with the consequence of additional verification factors (e.g. the gap factor for the influence of hole clearance of anchors) and justify the notice in FprEN 1992-4 (2016) “In applications where special considerations apply, e.g. nuclear power plants, modifications can be necessary”.

In addition to FprEN 1992-4 (2016) the superseded guideline ETAG 001 Annex E (2013) or TR 049 (2016) can be used for the seismic qualification of metal anchors. In this guideline two different seismic performance categories depending mainly on the earthquake strength (quantified by the PGA-value) are defined. These categories C1 und C2 result in different qualification tests assuming different crack width w_k: category C1 with w_k = 0.5 mm and category C2 with w_k = 0.8 mm. Consequently crack width analyses for the building elements with those metal anchors are to carry out to verify the compliance of the postulated crack width.

The adapted methodology for metal anchors also can be taken as a seismic qualification basis for headed studs and anchor channels. However, specific characteristics in comparison to metal anchors result in further specifications which require an additional expert report in general.

German DIBt-Guideline for metal anchors in nuclear power plants

The DIBt-Guideline (2010) is intended for the design and qualification of safety related metal anchors using in nuclear power plants. The design is based on the nuclear specific design requirements of DIN 25449 (2015) with regard to the partial safety concept of DIN EN 1990 (2010) including the different requirement categories A1, A2 and A3 (DBE: requirement category A3; see Fig. 4).

In addition to the design concept specified certification tests are prescribed in the DIBt-Guideline (2010), especially with regard to seismic action effects with resulting large cracks. The guideline defines anchor tests with a specified number of load cycles and crack opening cycles, which have to be considered by an assumed maximum crack width. So for example the load bearing of anchors has to be guaranteed in cracked concrete structures with crack openings up to a crack width of $w_2 = 1.5 \cdot w_k$. That means that the suitability of a metal anchor is checked for a crack width w_k which corresponds to the characteristic load carrying capacities. The standard value for the crack width amounts to w_k = 1.00 mm. Lower w_k-values require additional crack width verifications for the particular building.

The application of the DIBt-Guideline (2010) is not confined to metal anchors, because the fundamental requirements of this guideline can be applied also for other fastening types. So for new build projects in German nuclear power headed studs and anchor channels have been qualified on the basis of the DIBt-Guideline (2010) regarding additional expert reports, which considered additional specifications. For example, in 2010 the application of Halfen anchor channels HZA-PS in a new emergency diesel building of the German nuclear power plant Isar 1 was approved by an evaluation report of Block et al. (2010), regarding the test requirements of the DIBt-Guideline (2010).

CONCLUSION

For the compliance of the protective goals of nuclear power plants (controlling reactivity, cooling of fuel assemblies, confining radioactive substances and limiting radioactive exposure) safety-related components and building structures as well as safety related fastenings are defined with the consequence of a necessary seismic design. Such a seismic design is based on a site specific design basis earthquake (DBE) as an input for a safety orientated seismic calculation procedure for the determination of the particular action effects. Generally, this procedure considers partial structural models with inherent safeties where the safety related fastenings and their seismic action effects are standing at the end of the procedure.

Safety related fastenings differ according to cast-in fastenings like anchor plates with headed studs or anchor channels and post-installed metal anchors like expansion anchors, undercut anchors or bonded anchors. With regard to seismic design safety related fastenings are to be qualified for seismic action effects, especially for seismic induced large crack openings. Qualification and design demands are provided in European guidelines and standard, which correspond to the safety concept of the Eurocodes defined in EN 1990 (2010). In addition the seismic design requirements of the nuclear safety standards need to be considered. One of these standards is the German DIBt-Guideline (2010), which provides demands on the design and qualification of safety related metal anchors using in nuclear power plants.

With regard to new build projects the demands on the seismic design and qualification of fastenings illustrates the importance of an anchoring concept at an early stage of the detailed design process. Such an anchoring concept also shall consider load margins and possible flexibilities for anchoring of components to support an efficient ageing or lifeteime management during the operation phase of a nuclear power plant.

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