Impact Resistant Superstructure for Power Plants Part II: Structural Concept and Global Response

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Abstract
The paper presents a comprehensive structural concept of a modern impact resistant superstructure together with the investigation of the global mechanical impact response. The superstructure provides a satisfying protection against local and global damage as well as a significant reduction of aircraft induced vibrations by its design and foundation concept. Large scale high performance concrete (HPC) box girder substructures are monolithically connected to form a spatial superstructure. The double-walled (multi-layer) box girder substructures are ensuring both the overall shear and bending resistance against aircraft impact as well as the large self-supporting spans over the existing facalities to the lateral foundations. With the application of ductile and high strength fiber reinforced high performance concrete materials multiple goals for an improved impact and fire resistance as well as an optimized weight to stiffness ratio are achieved to realize the large free-spans. Hence the resulting superstructure is kept very efficient in geometry, weight and constructability allowing for established and accepted construction methods and a potential additional use of large spaces such as storage and machinery.

Keywords: nuclear power, decoupled external super structure, aircraft protection, HPC/UHPC, box girder

1 Introduction

Some building structures of early generation boiling water reactors need external measures to protect critical components from severe damage and vibrations caused by an aircraft impact. In contrast to recently applied - non-structural - measures like smoke screening or GPS-camouflage, physically decoupled external superstructures potentially provide a direct and effective protection of critical plant components and important supply lines. However the erection of such an external superstructure on an existing site is influenced by numerous geometrical, technical, economical and regulatory conditions.
Hardening of early plant generations requires additional protection structures to cope with the huge dynamic forces and momentum. In the paper a new concept for an external superstructure to protect a boiling water reactor without direct contact to the existing facilities on site has been developed. The bridge-type, hollow box girder structure is illustrated in FIGURE 1 (left). The local structural resistance against aircraft impact is based on a multi-layer approach of the external and internal high performance concrete walls of the box girders. The associated method is described in part I of the papers [Rie11]. The multi-layer approach is essential to realize the free-spanning overall structure since the existing plant and its operation license must be virtually unaffected by the construction in the erection phase and after completion.

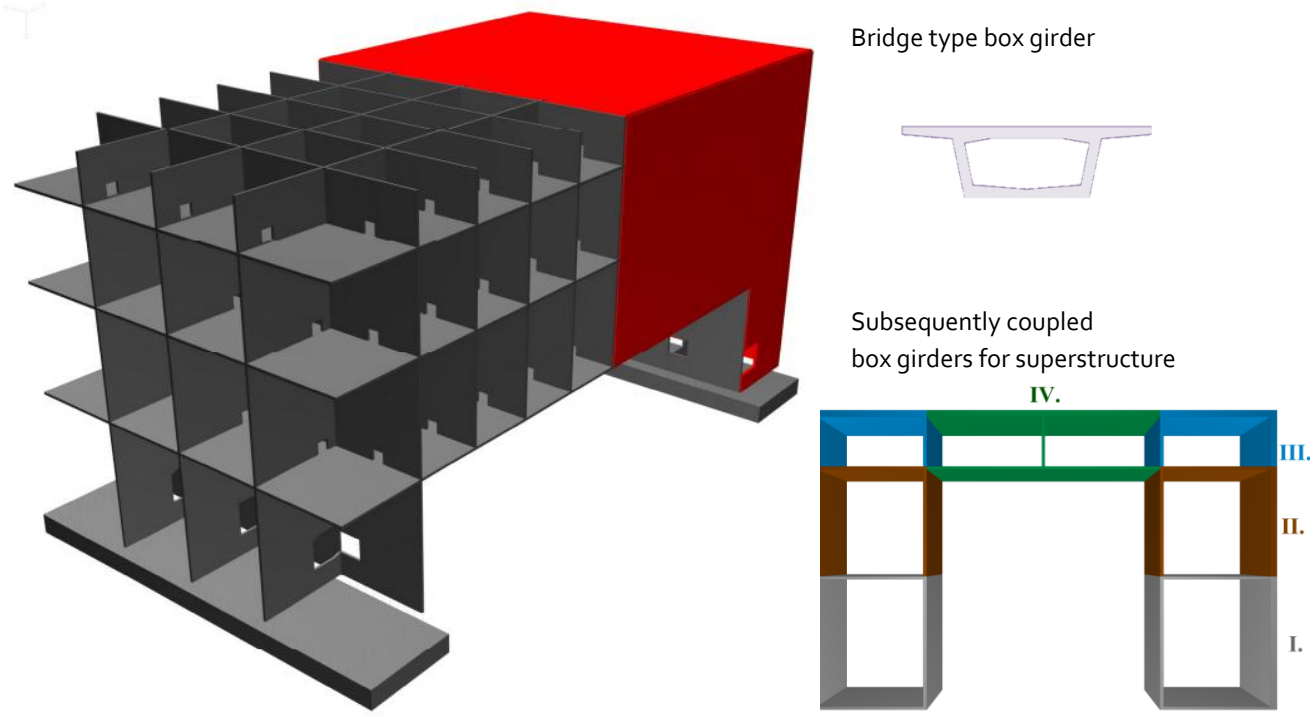


FIGURE 1: Left: Self-supporting superstructure consisting of a protective wall in Ultra High-Performance Concrete (red color) and an internal box girder structure (grey color), Right: Cross sections of a typical bridge type box girder (upper) and development of spatially coupled box girders for the superstructure (lower)

Once the (Ultra) High-Performance Concrete walls are designed against local perforation the dynamic forces and momentum have to be covered by a self-supporting global structure crossing the large span of more than 100m. In addition to resulting high dynamic structural forces the local damage caused by aircraft impact has to be taken into account in a geometrically and timely accurate numerical simulation. The concept of the superstructure and the associated investigations of the global response are explained in detail in the following chapters 2, 3 and 4.

2 Structural Concept

2.1 Box girder substructures

Box girder structures are usually applied in bridge design to realize large self-supporting superstructures across rivers, valleys or important transport ways. Over the past centuries support-free technologies have been developed to erect such structures without any contact to the ground such as the incremental launching method and the cantilevered construction method. Box girders consist of an upper and lower flange and at least two connecting shear walls which can be used for very large spans as they combine a high stiffness with a low weight (FIGURE 1, upper right). At the same time they are very effective against local damages as loads can be redistributed to other parts of the box girder [Noe10]. Based on these fundamental properties a new type of large scale box girder structure was developed for the superstructure to cover both vertical and horizontal loads caused by an aircraft impact. The box girders are furthermore strengthened by lateral vertical and horizontal shear walls in equidistant distribution over the girder length to enhance the local and global stiffness, ductility and redundancy (chapter 2.2).

The segmentation in box girder substructures enables for a stepwise erection process. The erection starts with a single box girder subsystem (FIGURE 1, lower right with Step No. I in Illustration) being built as a cantilever structure outside the existing site and processed sidewise from the external towers until the gap closing is reached. After finishing this first box girder a safe work level is provided to build the upward spatial structures using conventional R/C building techniques

(Steps No. II-IV in Illustration). The double wall concept of the symmetrical box girders provides three benefits:

- longitudinal stiffness for large free spans
- lateral stiffness against horizontal impacts
- resistance against local perforation with a minimized wall thickness

2.2 Redundancy elements in the spatial superstructure

Additional redundancy is achieved by integrating lateral monolithically coupled walls in equidistant distribution over the whole spatial structure. As a consequence, local damage caused by an aircraft impact can be compensated by load and stress redistribution to avoid disproportionate collapse of the whole structure. The equidistant distribution of these redundancy elements leads to a uniform perforation resistance at every individual point on the external surface hence weak areas in the structures are minimized. Based on this concept, only three characteristic impact scenarios have to be distinguished: plate impact, T-wall-impact, edge-impact. The associated design for these three impact scenarios are described further on in chapters 3 and 4.

2.3 Towers as large scale supports for spatial loading founded on decoupled raft foundations

Outside the existing buildings two spatially stiffened R/C towers are built initially on raft foundations as large scale supports (combutments) for the spatial superstructure. The towers are also strengthened by the equidistantly distributed lateral walls as the have to provide the same perforation resistance and redundancy against local damage caused by any lateral aircraft impact.
The raft foundations are very effective to take all horizontal impact loads with a minimum of deformation. The weight/bending moment ratio of the global structure under aircraft impact ensures its stability against overturning. Concurrently, the high vertical loads have to be safely transferred into the local ground so that a sufficient footing has to be provided in compliance with the facility and respective boundary conditions on site. The choice of decoupled raft foundations leads to

- an equalization of high local soil pressures
- the possibility to keep important local functions such as coolant water pipes at their original location
- a non-iterruptive erection and completion phase
- a minimization of horizontal deformations
- a maximum reduction of impact induced vibrations

The latter aspect is decisive as aircraft impact induced vibrations are not necessarily enveloped by a dynamic earthquake design as FIGURE 2 shows. The peak spectral accelerations occur at different frequencies (30-50 Hz) so that further reduction is needed to protect important facility components. As a consequence the external superstructure is decoupled from any solid existing building to take advantage of the soil damping.

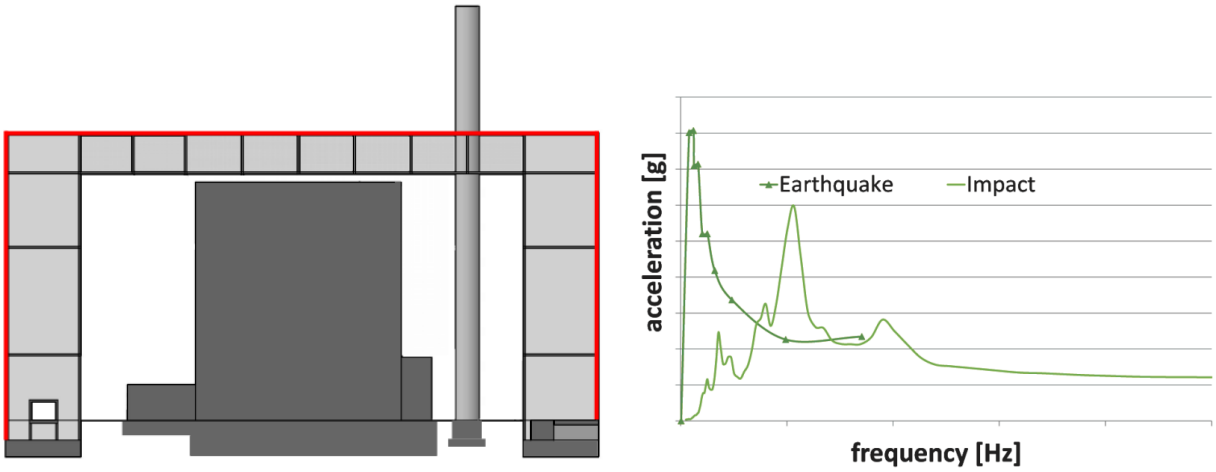


FIGURE 2: Left: Raft foundations of superstructure are physically decoupled from the existing plant; Right: Calculated acceleration spectra due to earthquake and aircraft impact

3 Investigation of global structural response –superstructure design by FE-simulation

3.1 Design objectives and strategies

The primary design objective of the external superstructure is to physically protect defined critical facilities against direct impact of aircraft components, debris, induced vibrations and fire. Against this background an effective minimization of material resources for the superstructure can be achieved by allowing for a certain local damage to the external structure. However, disproportionate effects such as further structural collapse or the damage of parts of the facility has to be avoided by a robust design of the global structure. Comparable design strategies can be found in international recommendations [Ni07] in context with modern design strategies against malicious threats. Dynamic design loads can be obtained from common standards such as [DIN08]. It has to be noted that these load-time-histories are based on an aircraft impact onto an ideally rigid target. Elastic and plastic deformations of targets have to be quantified separately in dynamic calculations [see e.g. Kru02] as they may influence the energy dissipation of the whole impact process significantly [Su93].

Based on these design objectives and strategies the robustness design concept for the external superstructure allows for a local vulnerability to the external wall and parts of the lateral redundancy walls together with a robustness design of the global structure.

As the structural impact boundary conditions are similar over the whole periphere it is possible to define three characteristic local subsystems to be investigated (FIGURE 3). Plate-impact, T-wall-impact, Edge-impact. The numerical simulation is computed in two subsequent steps:

1. A hydro-code simulation of the local highly nonlinear impact process leading to a damage profile and residual loads which act onto the global structure (see Part I)
2. A structural dynamic simulation of the whole superstructure including the soil-structure interaction (see chapters 3,4)

With the help of preliminary calculations the area with a strongly nonlinear material behavior has to be separated from the surrounding linear elastic material behavior. This information is subsequently transferred to the global structure for the three different impact subsystems with respect to local damage, plasticity, mass conservation and residual load transport in time and space.

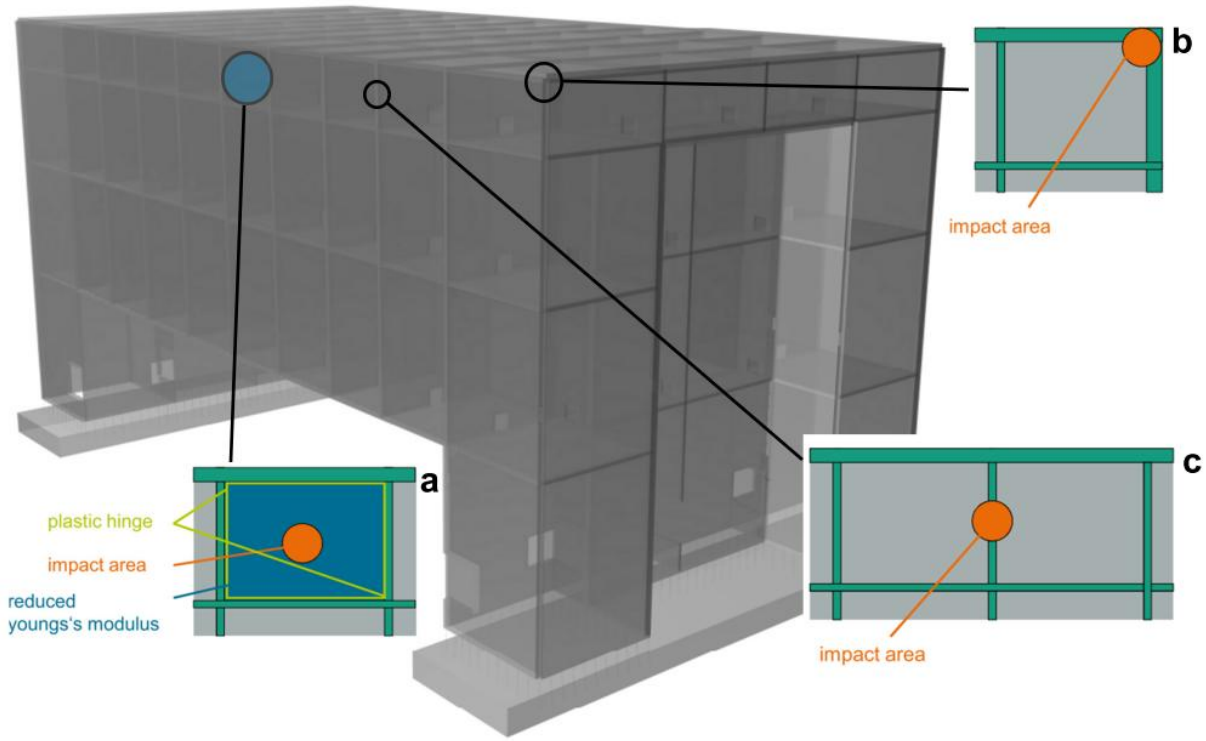


FIGURE 3: Integration of local damage in the global structural model for the three characteristic impacts: plate impact (a), edge impact (b), T-wall impact (c)

The impact in the center between lateral stiffening walls ("plate impact") is characterized by large plastic deformations perpendicular to the plate axis which occur together with plastic hinges at the adjacent lateral walls. Furthermore a significant amplitude reduction and time delay of the transferred load-time history can be observed due to the energy dissipation of the plate. These aspects are simulated in the global system by iteratively adapted local stiffnesses and instationary load-time histories obtained from the nonlinear hydro-code simulations. Hence the most important physical properties – mass and momentum conservation, energy dissipation and load-time-history and initial material state for the dynamic calculation - are transferred most accurately from the local to the global system.

In contrast to the field center, the impact onto rigid T-junctions or edges of several lateral walls causes only minor plastic deformations. With respect to induced vibrations the initial load-time history of the aircraft is hardly influenced. However the external wall and the immediately involved lateral walls are locally damaged. Such rigid impact scenarios are simulated by applying an unchanged, initial load-time history and a partly reduced stiffness of damaged elements to the global system.

3.2 Finite-Element-Simulation

The global structure is calculated in a structural dynamic Finite-Element simulation. All parts of the spatial structure contribute to the spatial resistance as their thickness leads to a considerable perpendicular stiffness. Hence they are discretized by spatial shell elements. The numerical time step calculation of the dynamic process is driven by the instationary load-time history introduced at time step t_0+1 to a previously intact global system subjected to an initial stress and deformation state at time step t_0. The initial state includes all dead loads and permanent live loads according to the exceptional load situation in [DIN08].

In the integration method the equation of motion is implicitly solved for each time step Δt. In order to represent the structural dynamic behavior of all relevant structural elements the individual eigenfrequencies and longitudinal material soundspeed $c_{L,S}$ have to be considered in the geometrical (eq. 1) and the time discretization over the impact duration T_P and structural oscillation (eq. 2).

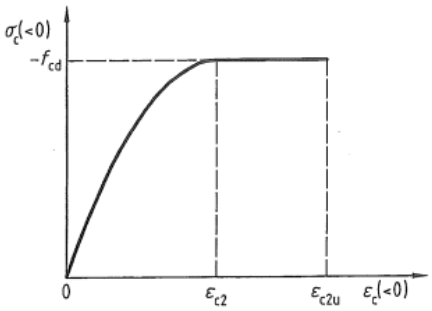
$$L_{n,S} \le \frac{1}{8} \cdot \frac{c_{L,s}}{f_n} \quad (1)$$

$$\Delta t \le T_p / 10 \quad (2)$$

In contrast to the local impact area the strain-rates which occur in the adjacent structural elements do not significantly influence the material properties. However an appropriate nonlinear quasi-static material description for Ultra-High and High-Performance Concrete materials has to be applied. Recently several European and international studies [Sc08, Noe11, Rie10] have led to experimentally validated calculation values shown in table 1.

TABLE 1: Material data for Ultra High-Performance Concrete taken from [Sc08, Noe11]:

		C35	C100	C160
Young´s Modulus	[MN/m²]	29900	45200	50000
f_{cd}	[MN/m²]	35	100	160
ε_{c2}	[-]	-2.0	-2.2	-2.2
ε_{c2u}	[-]	-3.5	-2.2	-2.2
$c_{L,s}$	[m/s]	2900	3000	3300



It has to be noted that in the recent two decades several large building projects were successfully conducted with high-performance concretes as the material combines improved properties such as strength, compactness and durability. International experiences and use in structures are well documented in [Sc08] with referenced literature.

The FE supported design procedure of the global structure combines a large variety of impact cases to fulfill the defined design objectives. The three previously described impact types are applied to characteristic areas on the global envelope of the superstructure. The governing design criteria of all structural elements outside the highly nonlinear impact area are related to the exceptional-design-situation in [DIN08] in conformity with European standards.

$$E_d = E\left\{G_K \oplus P_K \oplus A_d \oplus \psi_{1,1} \cdot Q_{k,1} \oplus \sum_{i \ge 1} \psi_{2,i} \cdot Q_{k,i}\right\} \le R_d \quad (3)$$

In (3) A_d represents the instationary load-time-history on the initially loaded system with characteristic dead loads G_K and permanent live loads Q_K. The resistance R_d has to exceed acting forces E_d at any timestep and location over the time history until a final equilibrium is reached. Material nonlinearity is used along with the assumption of a linear elastic structural behavior according to (conservative) design standards such as DIN08 or Eurocode 2.

As this design method allows for concrete cracking structural damping is considered according to the adapted design code [DIN08] in a medium range of 5 % including the global damping effect of the soil-structure-interaction.

The finite element model includes the effects of the soil-structure interaction implicitly by defined boundary conditions. These boundary conditions are derived in separate dynamic numerical simulations using a nonlinear soil model and established dynamic engineering methods [DGGT02]. Both methods are based on the dominant dynamic soil properties: the dynamic Young´s and shear moduli E_{dyn} and G_{dyn} defined by the shear wave velocity v_s , the Poisson's ratio ν, density ρ and the reference stress σ_{at} (see Eq. 4).

$$G_{dyn} = \rho \cdot v_s^2, \quad E_{dyn} = \rho \cdot v_p^2, \quad E_s = v_e \cdot \sigma_{at} \cdot \left(\frac{\sigma'}{\sigma_{at}}\right)^{w_e} \quad (4)$$

4 Investigation of global structural response - Results

FIGURE 4 shows a representative result of the aircraft impact in the central upper part of the structure with the maximum deformation of the whole structure in impact direction. This peak deflection is limited to less than 1/5000 so that the whole structure performs with very small oscillation amplitudes. The illustration shows that apart from this moderate global oscillation the structural elements especially in the vicinity of the impact area show larger oscillations. The maximum deflections are reached with the expected time delay to the instationary load-time history still remaining in the regime of up to l/150 so that a satisfying resistance can be expected as long as the ductility of the fixed supports are ensured by the longitudinal and transverse reinforcement design.

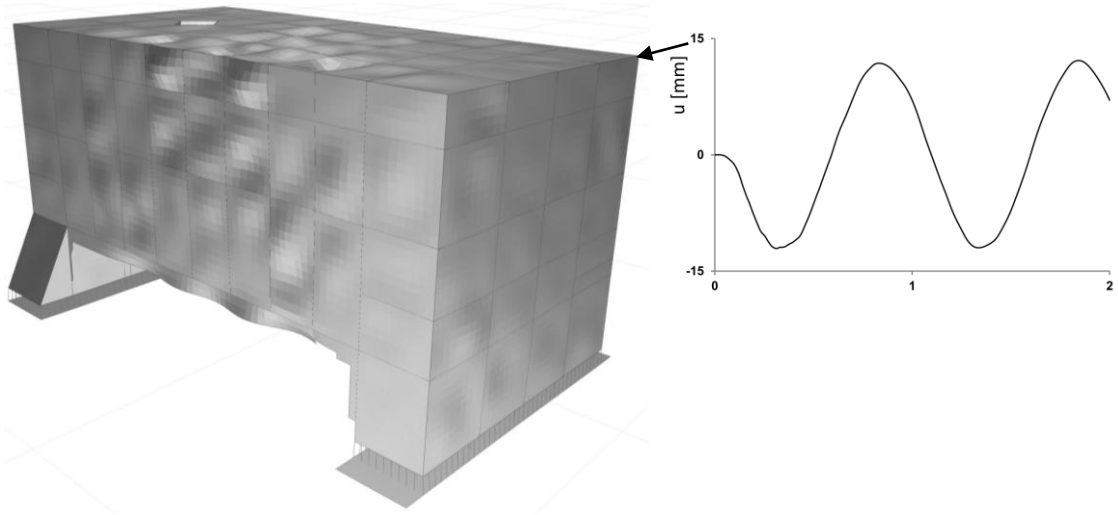


FIGURE 4: Deformations in global structure at timestep n, local and global oscillations in linear elastic regime of the R/C structure; global deformation graph with top deflection of 12 mm maximum

The superposition of the large variety of characteristic scenarios finally leads to the reinforcement of all structural elements (FIGURE 5). It has to be noted that for important structural elements such as the external wall the reinforcement for local perforation resistance is partly higher than the reinforcement for the global design. The reinforcement ratio is typical for aircraft impact resistant structures while the element thicknesses are well reduced due to the application of high-performance concretes.

Apart from the impact resistance the long-span superstructure is designed for it´s dead and permanent live loads which lead to high tensile reinforcement in the central lower part of the superstructure in Figure 5 at the location of maximum bending moment (marked by the red colour). A further increase of the wall thickness (e.g. due to the application of conventional concrete) would lead to a significant increase of weight which can hardly be applied to such long-span structures.

Earthquake design situations were investigated as well to prove that the comparatively massy structure is capable to resist relevant earthquake scenarios. The underlying horizontal ground acceleration was chosen to 2 m/s².

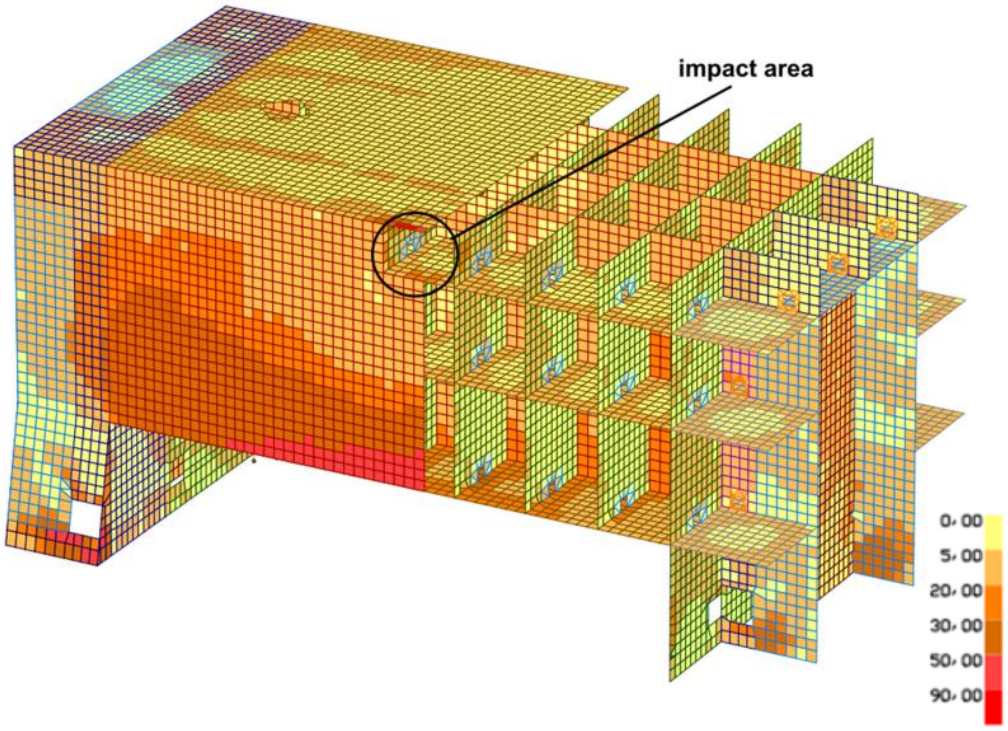


FIGURE 5: Reinforcement for a representative impact scenario by global design. Local design reinforcement is for most elements significantly higher (see Part I)

Additional investigations were conducted for the T-impact and edge-impact scenarios for additional loads invoked by geometric nonlinearity. Such stability problems are not covered by the dynamic Finite Element analysis. As the impact might occur close to a perpendicular wall the whole momentum has to be taken by one single lateral wall. A simplified subsystem of the lateral wall is defined (see FIGURE 6 right). The geometric nonlinear calculation is conducted under statical conditions so that the dynamic load factor for the transient load-time history has to be determined over the eigenfrequency spectra using Eq. 5.

$$DLF = \frac{x_{max}}{x_{stat}} = \frac{x_{max}}{\left(F_0 / K\right)} = \frac{x_{max} \cdot K}{F_0} \tag{5}$$

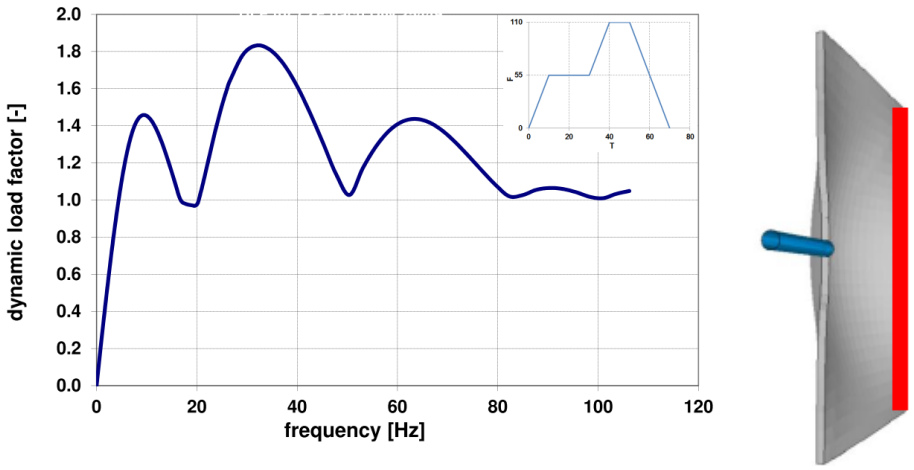


FIGURE 6: Dynamic Load Factor (DLF) for the impact function in DIN 25449 for structural eigenfrequencies between 1-100 Hertz and structural system for the numerical simulation of lateral redundancy walls (stability problem)

The geometrically nonlinear FE calculation is launched by a small initial imperfection and solved iteratively until the equilibrium conditions are fulfilled. With a wall thickness of 0.5m (High-

Performance Concrete) the resulting reinforcement of 1.0 vol.-% is distributed symmetrically on both sides of the wall to satisfy the stability criterion.

5 Conclusions

A large span length of ~ 100m, contact free superstructure across existing plants is possible by using ultra-high performance concrete materials for spatially connected box girders providing a satisfying resistance against lateral aircraft impact. Based on established bridge builing techniques a new multiple box girder type was developed and proven by local and global FE-supported design calculations as an adequate system to resist against lateral aircraft impact scenarios. With the application of modern ductile high performance concrete materials (HPC) a satisfying weight/stiffness ratio can be achieved to realize large free spans over an existing facility. Together with the addition of equidistant horizontal and vertical lateral walls it could be proven that the superstructure is well suited to ensure the local perforation resistance and the robustness against the resulting local damages at any timestep and location efficiently. The impact resistant concept is used for the lateral supporting towers of the superstructure in the same way to provide sufficient resistance over the whole building peripher. Based on raft foundations which are physically decoupled from any existing building it was proven that aircraft impact induced loads and deformations as well as impact induced vibrations can be safely transferred into the soil.

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