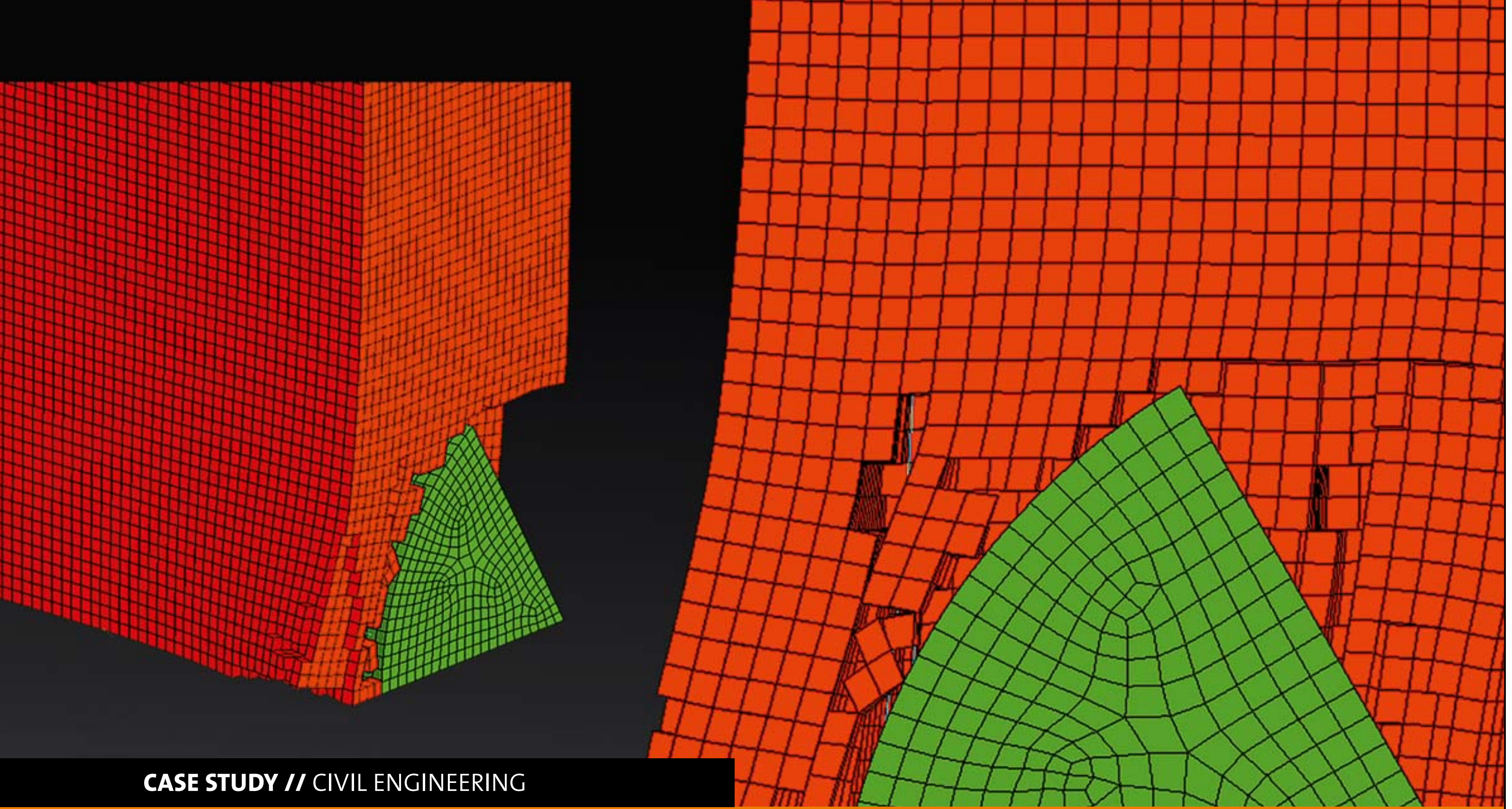


SIMULATION OF BURST PROTECTION WITH ANSYS LS-DYNA AND OPTISLANG

Using ANSYS LS-DYNA and optiSLang, impact simulations were conducted for the proper design of burst protection walls made of reinforced concrete in turbomachinery test facilities.

Motivation and task definition

Rotating machines, e.g. turbines, generators and aircraft engines, are operated at high speed in real use as well as in rotary test facilities. In the event of a component failure (case of accident), persons and material in the immediate surrounding must be protected from the effects of flying debris by suitable burst protection devices [1]. For the burst protection of test facilities, either an immediate encapsulation of the rotating machine or the installation of separating walls, e.g. between test and measuring facility, can be considered.

In case of an accident, it is assumed that bursting fragments of the rotating machine will hit the protection walls at high speed. The wall thickness has to be dimensioned in a way that fragments cannot punch through or cause chipping on the off-load side.

This article presents a procedure for the design of burst protection walls made of reinforced concrete which are suitable for rotary test facilities. A sufficient dimensioning can be verified by means of non-linear, transient dynamic studies using ANSYS-LSDYNA as well as by conducting a subsequent sensitivity analyses for different load scenarios with ANSYS-optiSLang.

Simulation solutions

Assumptions for the description of the load scenario

Impact loads on burst protection devices are considered to be accidental design situations according to DIN EN 1991 [2]. The load specifications (e.g. breakage and flying debris of turbine blades or fragments of rotating disks) must be defined according to available standard assumptions (e.g. [1], protection category D), engineering assumptions as well as experience of the plant operator. Sensitivity analyses, carried out with ANSYS optiSLang, revealed the influence and the effects of individual load assumptions on the burst protection device.

In this case, a third slice load fragment was chosen (see Fig. 1) as a basis for the impact definition. The full rotational energy of the third slice is supposed to be converted into translational energy, from which a corresponding translational initial speed for the impact of the fragments on the wall is derived. The largest rotational energy of the different experimental devices defines the worst case scenario. The stiffness of the fragment is assumed with the Young's Modulus of steel (210000 MPa). A plastic energy dissipation of the fragment is not considered.

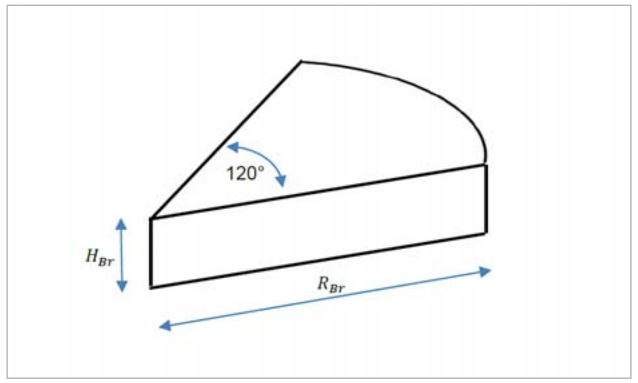


Fig. 1: Geometry of fragments (schematic illustration)

Non-linear resistance of reinforced concrete under impact load

The description of the non-linear resistance of reinforced concrete is based on the normative specifications in DIN EN 1992 [3] with consideration of [4] for non-linear methods (see section 5.7). The material properties of the concrete and reinforcing steel according to [3] are used for the respective concrete or reinforcing steel class, as well as the partial safety factor for resistence γR = 1,1 required for accidental design situations.

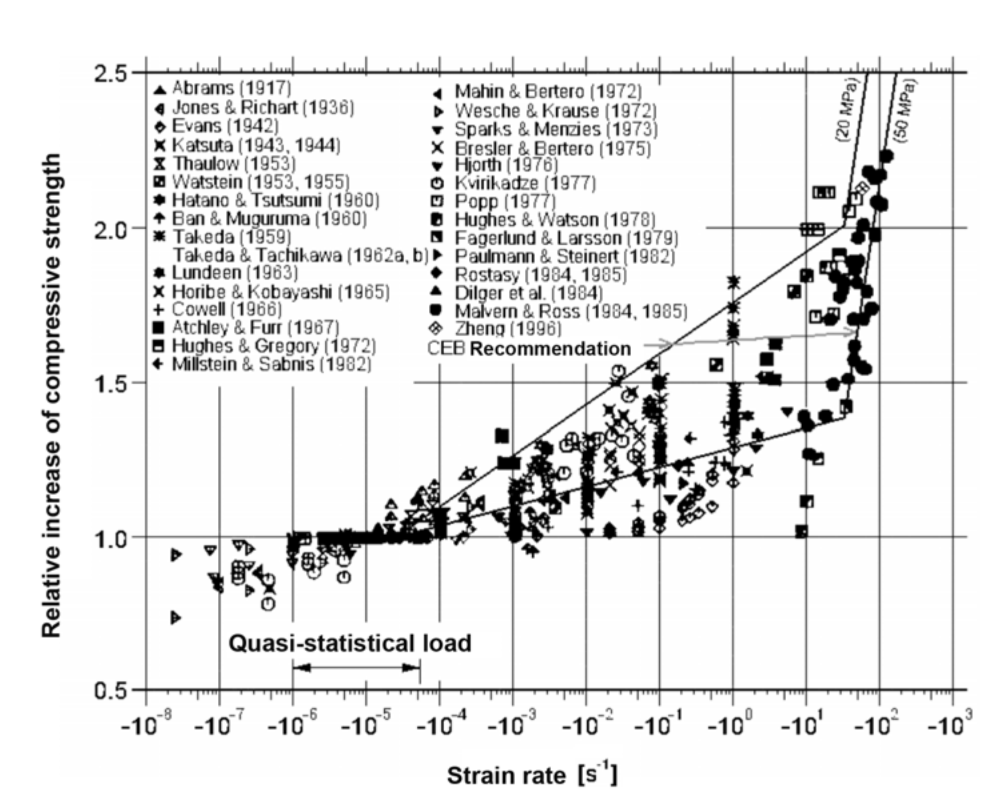
However, the normative specifications still need to be extended for this transient dynamic impact anaylsis. Regarding concrete and reinforcing steel, a strain rate-dependent increase in strength can be particularly observed under impact load. Among other things, this effect was analyzed for concrete in [5]. In order to take this effect into account in the FE analyses, the strain rate-dependent increase of concrete compressive strength is considered according to the CEB recommendation for concrete with a compressive strength of 50 MPa, specified in [5]. The correlation can be seen in Fig. 2.

For concrete, the elasto-plastic LS-DYNA material model * MAT_PSEUDO_TENSOR with Mode II.C. ("Tensile failure plus damage scaling") [6] is applied. Therein, the shear failure of the concrete is described by an elliptical flow condition and the softening by means of a damaging function.

The non-linear material behavior of the steel is represented by the LS-DYNA material model * MAT_PIECEWISE_LINEAR _PLASTICITY [6]. The strain rate dependence is derived according to [7] with a strengthening coefficient of about 1.15 at a strain rate of 10 s^{-1}. A multilinear stress-strain curve is defined, taking into account a softening caused by the effect of reinforcing steel necking. If a failure strain of 6% is reached, the elements become deleted from the system (eroding).

Finite Element simulation model

The burst protection walls made of composite reinforced concrete are represented by a discrete, spatial modeling of concrete and reinforcing steel. Steel bars were chosen for the reinforcement of the burst protection walls. The concrete is discretized by volume elements, the individual rein-



Strain rate [1/s]	Factor
1E-08	1,00
3E-05	1,00
35	1,38
160	2,50

Fig. 2: Dependence of concrete compressive strength on the strain rate according to [5] (Fig. 2.18)

forcing bars by means of beam elements. A complete bond between reinforcing steel and concrete is assumed and implemented in the FE model by the use of equal nodes of the concrete's solid elements and the beam elements of the reinforcing steel.

The finite element model (FE model) is shown in Fig. 3. For the design of the burst protection walls, the FE model is parametrically created, thus the wall thickness, the reinforcement ratio, the type of concrete, the place of impact, as well as the load parameters of the fragment can be varied.

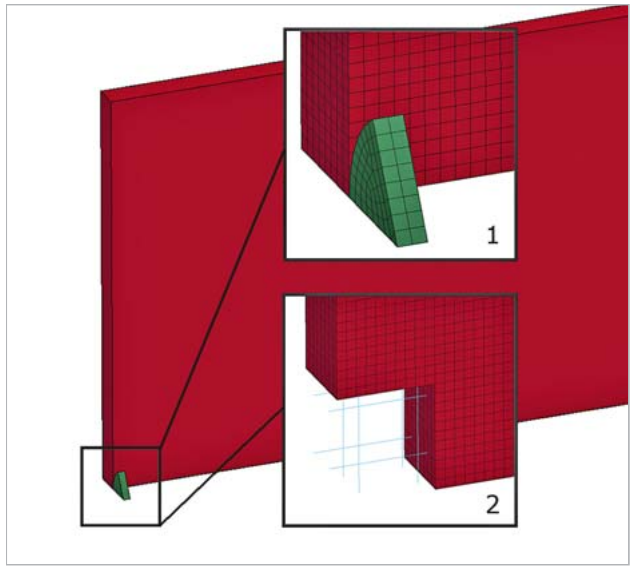


Fig. 3: Double-symmetrical FE model of the burst protection wall; 1-fragment, 2-reinforcement

Definition of boundary conditions

The horizontal load transfer of the burst protection walls is via the floor and transverse walls, as well as over the cover plate (at test stand 1) or the ceiling (at test stand 2). In the FE model, the effects regarding the cover plates on the booths in test stand 1 are idealized by two limit states (two analyses). In the first analysis, the burst protection wall is assumed to be supported by the cover plate perpendicular to the surface of the wall. Thus, a four-sided supported wall is applied in the finite element model. The impact position of the fragment is defined vertically and horizontally in the center of the burst protection wall, as this is assumed to be the worst-case impact position for a four-sided supported wall.

In the second analysis, the supporting effect of the cover plate is unconsidered, which is represented by a three-sided supported wall in the FE model. Here, the impact position of the fragment is located vertically on the upper edge (unsupported edge) and horizontally in the center of the burst protection wall, which is assumed to be the worst-case impact positions for a three-sided supported wall.

Those booths of the test stand 2 which are all covered with a ceiling are represented by a four-sided supported wall in the FE model. The impact position of the fragment is applied analogously to the first analysis at test stand 1 vertically and horizontally in the middle of the burst protection wall. Corresponding symmetry conditions are used depending on the applied double-symmetrical or half model.

The load on the burst protection walls results from the mass $\mathbf{m}_{Br}$ and the initial speed $\mathbf{V}_{0,Br}$ of the fragments. The initial speed is derived from a translational energy, which is fully generated by the rotational energy of the fragment.

Simulation of design variations

During a first variant study, both the wall thicknesses from 150 mm to 500 mm as well as the reinforcement ratio are incrementally increased in order to determine the smallest thickness that is still capable of preventing fragments from punching through the wall. In addition, constructive boundary conditions (e.g. bar diameter, bar spacing, concrete cover) are considered in these analyses.

The analyses reveals that the impact position of the fragment has no relevant influence on the results. This can be explained by the conservation of momentum and the much higher mass of the burst protection wall compared to the fragment.

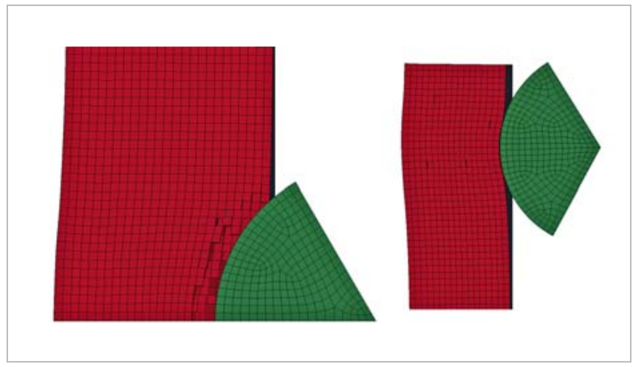


Fig. 4 Sample plots for the state of final deformation regarding an impact area located in the middle and at the upper edge

Sensitivity analysis

As a part of the sensitivity analysis, four parameters are varied which describe the shape as well as the kinetic energy of the fragment:

- the speed of the rotor, i.e., the translatory speed
- the radius of the fragment
- the height of the fragment
- the mass of the fragment

The sample selection was carried out with ANSYS-optiSLang by using Latin Hypercube sampling. This method generates uncorrelated, uniformly distributed input variables covering the specified variation ranges.

The aim of the sensitivity analyses of both test stands is to identify the initial kinetic energies of the fragments when the burst protection walls of the test cells are about to break or chipping starts on the off-load side. For this purpose, response values of the penetration depth of the fragment and of the maximum kinetic energy are determined. In addition, a visual examination of the damage is done by evaluating the plots from the off-load side of the wall. The wall is considered to be inadmissibly stressed if it shows damage on the back side (stripped, accelerated fragments).

Some results are exemplarily shown in Fig. 5 and Fig. 6. The variation of the maximum penetration depth (parameter maxU) is influenced by the variation of the three input parameters mass, height and speed. As shown in Fig. 5 top, mass has the greatest influence with 53.5%, followed by speed with 33.1% and height with 19.8%. However, the variation of the radius has no relevant influence on the variation of the penetration depth. The results also indicate that the loading on the wall does not depend on the stiffness of the fragment but on its impact area. Fig. 5 bottom shows the Metamodel of Optimal Prognosis (MOP) for the maximum penetration depth as a result of the sensitivity analysis. The penetration depth (maxU) tends to decrease if the impact area (height of the fragment) rises. The influence of the height for smaller fragments is nearly linear. For a fragment mass approximately higher than 3 kg, the influence of the height shows exponential characteristics.

Fig. 6 shows the determined correlation between penetration depth and kinetic energy. Using these results, the plant operator is also capable of verifying future samples and load scenarios with regard to their impact on the demands of burst protection.

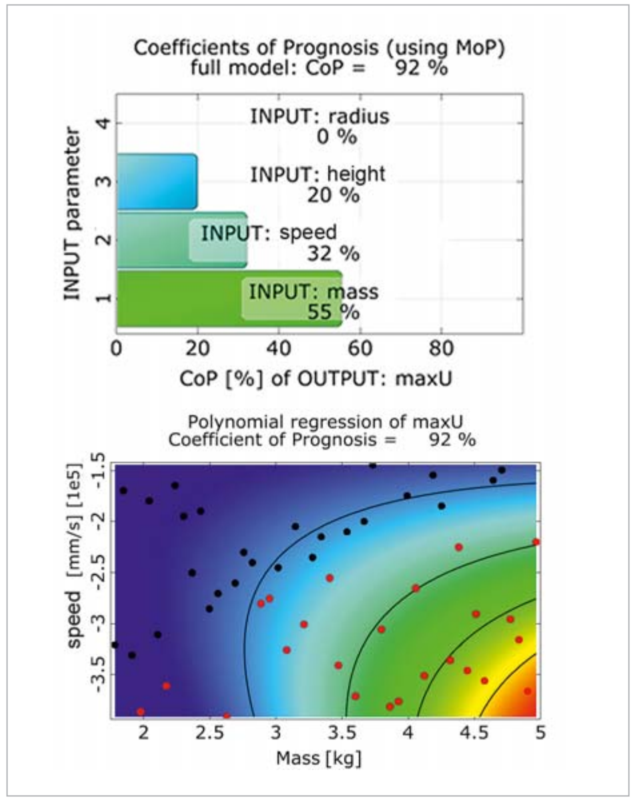


Fig. 5 top: Prognosis measures CoP of the penetration depth (maxU) compared to the input parameters; bottom: Metamodel of Optimal Prognosis (MOP) to visualize the dependence of the fragment's penetration depth regarding the load parameters v and m

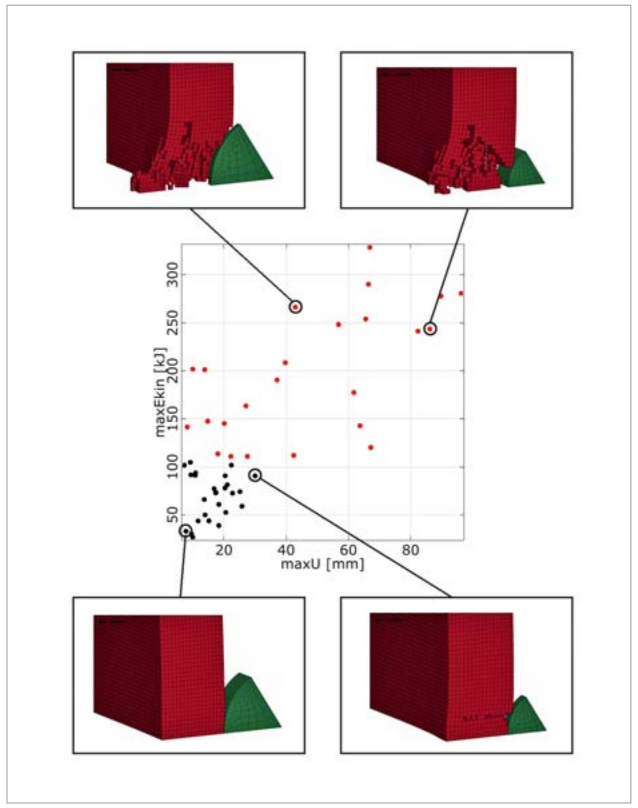


Fig. 6: Pairwise dependence of the kinetic energy regarding the penetration depth

Summary and conclusions

The presented simulation procedure supports the safe design of reinforced concrete burst protection walls according to the requirements of the operator.

Considering the ultimate limit state analysis (DIN EN 1992-1-1: 2011-01, Eurocode 2), a safety related to the actions on the structure could be determined. Besides a conservative description of the affecting loads, it is of crucial importance for such tasks to conduct a realistic simulation of the nonlinear material and crack behavior of the reinforced concrete. Here, a sensitivity study indicates the scattering ranges of load parameters with a sufficient burst protection. These results support operators of test facilities to quickly estimate permissible load scenarios for future tests.

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