Design and Full Scale Test of Blast Proof Concrete Containment with Steel fibres

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ABSTRACT: The beneficial effect of steel fibres regarding the dynamic properties of concrete is illustrated. First, the design requirements for the containment are explained. It will become clear that no save design can be archived with plain concrete and mild reinforcement only. The concept of design is illustrated, steel fibres and unbonded mild reinforcement are introduced. The main part is concerned about the nonlinear transient analysis, where the performance of the fibre reinforced concrete structure is computed in very detail.

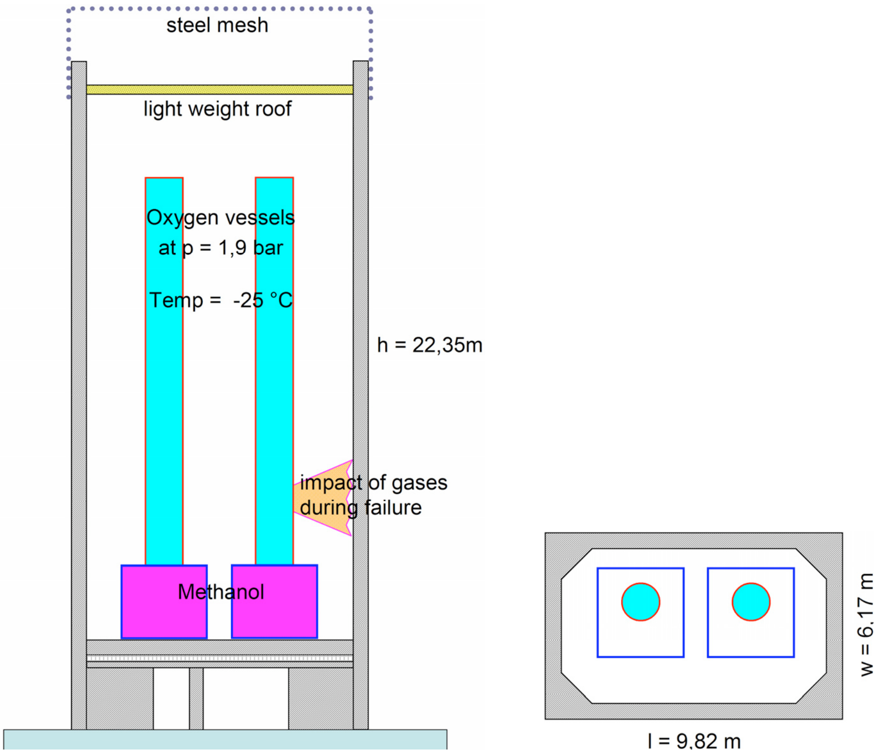
1 Introduction

A containment has to be designed for a hazardous chemical process (production of glyocyl acid). As long as the process is stable, there will act no forces but the dead load on the containment. But if the event of failure occurs a tremendous amount of energy will be released. (The energy is equivalent to two heavy duty trucks with 72 tons crashing into a rigid wall at a speed of 180km/h.)

A linear design which assumes tacitly that the structure remains fully undamaged after the event of failure was neither possible with available building materials nor required by the owner of the plant. However, a design requirement was that staff which can be present close to the plant must not be injured by detaching concrete boulders, etc. Thus, the question arises how to design a containment for impact loading which may be demolished after the impact but which must not endanger persons during the event of failure.

2 Concept of the plant

The concept of the plant is illustrated in Fig. 1. It is a hollow concrete tower with a light weight roof which will be lifted up by the pressure wave in the case of failure and caught again by the steel mesh. The height of the concrete tower is 22.35 m, the length is 9.82 m, the width is 6.17 m and the wall thickness is 50 cm. In order to conclude the laborious process of defining the impact, following impact got defined: 88,3 kg of exhaust gases at a speed of 1422 m/s for each vessel.



a) vertical section b) horizontal projection

Fig. 1 Layout of the plant for a hazardous chemical process

2.1 Choice of materials

It was proposed to build the tower with mild reinforced concrete. Since no parts shall be spalled off during the explosion, the brittle failure mode of concrete needs to be reduced. Thus, steel fibres are added to the concrete. Long steel fibres (Dramix RC-60/80-BN, [Bekaert]) got added at a dosis of 30 kg/m³ in order to dissipate as much energy as possible before a concrete boulder can be detached and to increase the compressive ductility of concrete as well.

Second, the tensile ductility of the structure should be increased to the maximum possible extent in order to be able to benefit from the inertia effect during the explosion as much as possible. Therefore, only the vertical and the minimum horizontal reinforcement got installed in the regular way and an extra horizontal reinforcement got covered by ducts in the middle region within the anchorage zones. This unbonded reinforcement is able to distribute high strains at a specific cross-section over the entire unbonded length of the rebar. Therefore, no local plastic hinge of the reinforcement may be expected.

3 Advanced analysis of the containment

As already explained, standard reinforced concrete designed by means of a linear analyses cannot solve the problem. The structure has to fail very ductile and this ductile failure mechanism has to be approached by the analysis model in order to account in the right way for the inertia effects. Since there is not really a save side in a dynamic analysis, advanced material models are necessary for predicting a correct structural response due to impact loading.

3.1 Concrete Model

Concrete is modelled in terms of plasticity. Crushing of concrete is controlled by employing the Ottosen failure criterion.

For tensile failure a rotating crack model is employed. It assumes the cracks perpendicular to the direction of principal axis. The law for tensile behaviour and crack opening is based on the cohesive crack concept and it is illustrated in Fig. 2 for plain concrete and for fibre reinforced concrete. Concrete is assumed to behave linearly elastic up to the tensile limit. The user can provide a tension cut-off factor ($1.0 \geq TCO > 0.0$) in order to scale the maximum allowable tensile stress. The tensile strength f_{ctm} must not be reduced since this would affect the compressive envelope as well. After a certain amount of tensile flow ε_{yt} has occurred, strain-softening is accounted for in a bilinear fashion in the context of the cohesive crack concept introduced by [Hillerborg] in order to be independent of the mesh size. The employed model is the one recommended in [MC90 and fib1]. In the implementation the stress obtained from the model is limited such that $TCO \cdot f_{ctm} \geq f_{ct} \geq rTCO \cdot f_{ctm}$. For fibre reinforced concrete, the same constitutive model can be used, only the parameter rTCO needs to be set according to the provided specifications for the fibres. In the present case $rTCO \cdot f_{ctm}$ = 1.14 MPa is assumed up to a strain of ε_{yt} = 10‰ and beyond that limit $rTCO \cdot f_{ctm}$ = 0.11 MPa is assumed as illustrated in Fig. 2. At unloading, crack closing is taken into account by reducing the plastic strain increment and a path as illustrated by the dashed line in Fig. 2 is followed. The amount of crack closing is controlled by β. An irreversible crack corresponds to β = 1.0 and a completely recoverable crack corresponds to β = 0.0. According to [Reinhardt and Dahlblom/Ottosen], β = 0.20 may give realistic results for plain concrete. For fiber reinforced concrete no recommendations for β seem to be available until yet. Since it is assumed that the values are higher than for plain concrete, β is varied between 0.20 and 0.40 in this work.

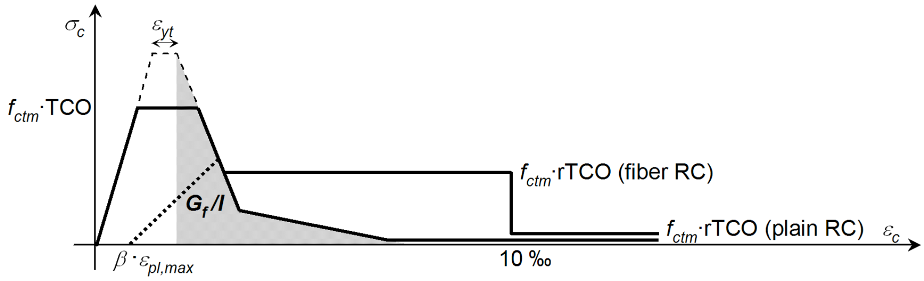


Fig. 2 Model for tensile failure of plain concrete and fibre reinforced concrete in principal direction

3.2 Modelling the bonded and the unbonded mild reinforcement

Rebars are embedded automatically into the parent element mesh for the concrete as illustrated in Fig. 3 without increasing the number of freedom [Hartl]. However, slip situations can be accounted for at the material level.

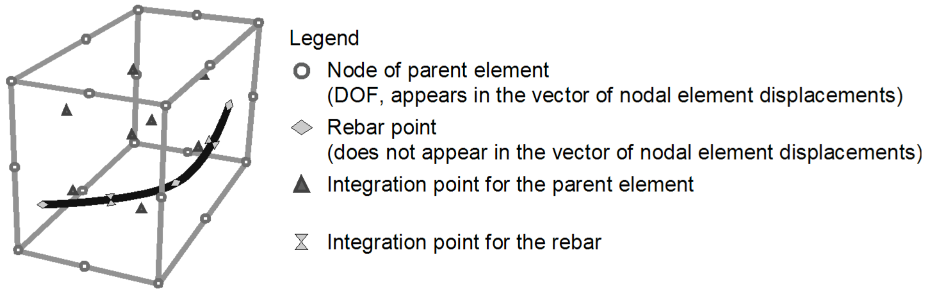


Fig. 3 Embedded reinforcement

3.3 Structural Response

The static performance for loading, unloading and reloading is shown in Fig. 4 and got computed by employing the finite element code BEFE [Beer], where the aforementioned computational models are implemented. A significant difference can be seen between the concrete which is reinforced with mild steel only and the fibre RC. Fig. 5 shows the strain in the reinforcement when the outward displacement of point 1 is 75 cm. The bonded reinforcement experiences close to point 1 a strain of 98 ‰ while the strain in the unbonded reinforcement is 14 ‰. Considering that the limit strain at the given strain rate of up to $\dot{\varepsilon}$ = 10 reduces about one third to 66 ‰ for TC 55 the beneficial effect of the unbonded reinforcement can be seen.

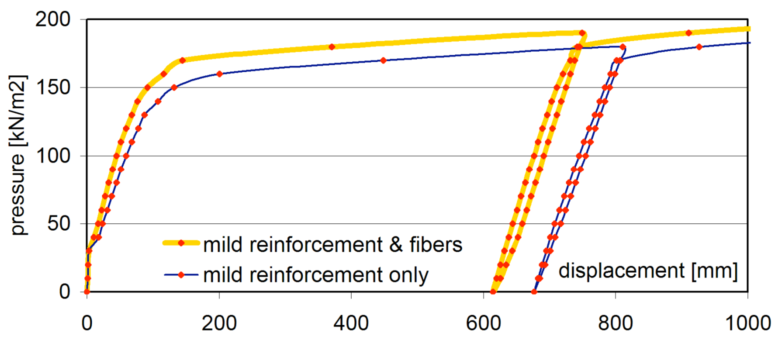


Fig. 4 Loading – unloading – reloading diagram

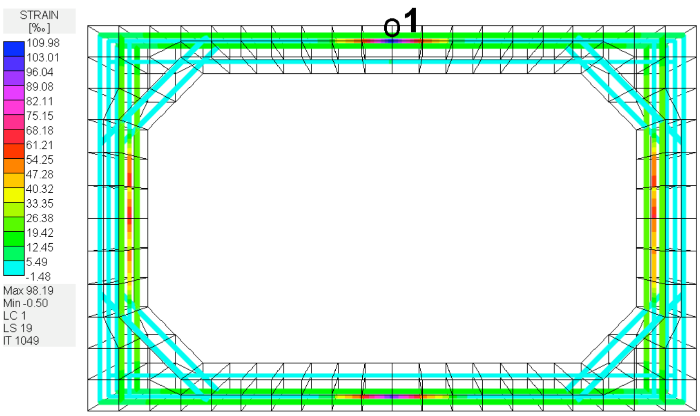


Fig. 5 Rebar strain at displacement u = 75 cm at point 1 of the fibre reinforced concrete containment

In order to point out the different tensile behaviour of plain concrete and fibre reinforced concrete, the compressive side was assumed to behave infinitely ductile. The compressive ductility of plain concrete and fibre reinforced concrete is compared in Fig. 6. Considering that the peak compressive strain at a displacement of 75 cm is in the order of -14 ‰, a brittle premature failure would be the consequence for plain concrete. However, fibre reinforced concrete will fail as well but due to the ductile post peak performance no concrete boulders are expected to detach in a brittle manner and a considerably amount of energy will be dissipated instead.

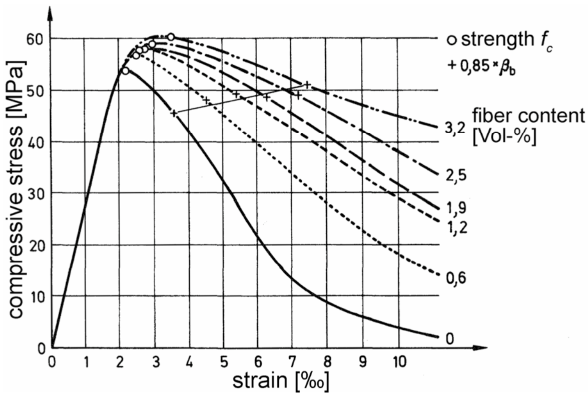


Fig. 6 Stress strain diagram of plain concrete and fibre reinforced concrete at compressive loading

3.4 Dynamic Analysis

The dynamic analysis is performed by means of a nonlinear single degree of freedom system, which is in this specific case a symmetrical system. The dynamic characteristics, i.e. concentrated mass and driving force got determined by means of a linear dynamic system. The design impulse of the impact got determined by considering basic principals of thermo-dynamics and gas-dynamics. It got verified by comparing the results to empirical ballistic recommendations and to findings obtained from a previous event of failure of such a plant. Since the time shift of the explosions in the two vessels is unknown, the time shifts are chosen such, that the deformation of the containment is either damped or amplified in other cases. As worst case scenario an explosion of both vessels at the same time is assumed. Fig. 7 and Fig. 8 illustrates cases where the displacement due to the second explosion is amplified by the first one for the containment with and without fibres. Comparing the maximum dynamic displacement with the according strains in Fig. 5 it can bee seen that a total loss of the structure is not expected, although a detrimental damage will occur. The fibres contribute significantly to reduce brittle spalling of concrete boulders.

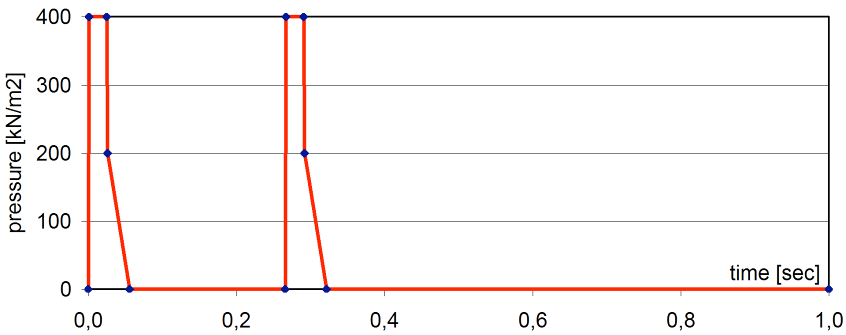


Fig. 7 Design impulse of the impact

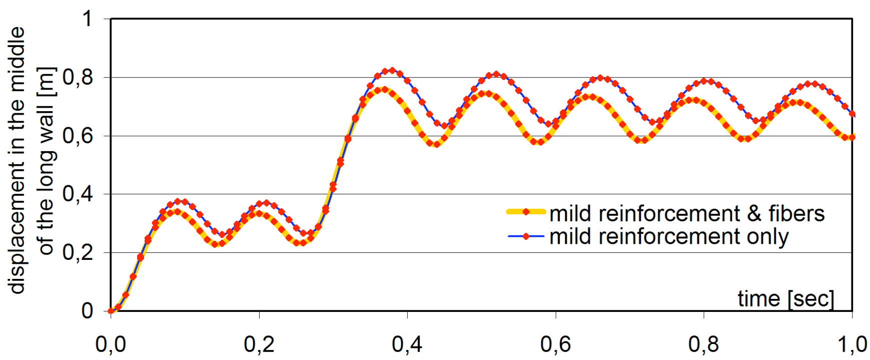


Fig. 8 Time displacement in the middle of the long wall due to the explosion

4 Event of Failure (Full scale test)

Three days after starting the plant the event of failure took place unfortunately and turned out to be a full scale test for the containment. The containment experienced a residual outward deformation of 15mm in the middle of the long walls and two considerably cracks at the same place. For the failure mode occurred the predicted impulse during the design process was between 2 x 2900 and 2 x 5300 Pa·s, that is considerably lower than the design impulse for the worst case scenario. The reanalysis of the impact has shown that the impulse acted had to be 2 x 4650 Pa·s in order to obtain 15 mm residual deformation, compare Fig. 9. Fig. 10 shows the computed crack pattern which is as well in good agreement with the observations on site. Thus the design assumptions are in good agreement with the observations. Fig. 11 shows a detail of the concrete wall. It can be seen that concrete parts are still connected to the containment via the fibres, thus no brittle detaching process took place.

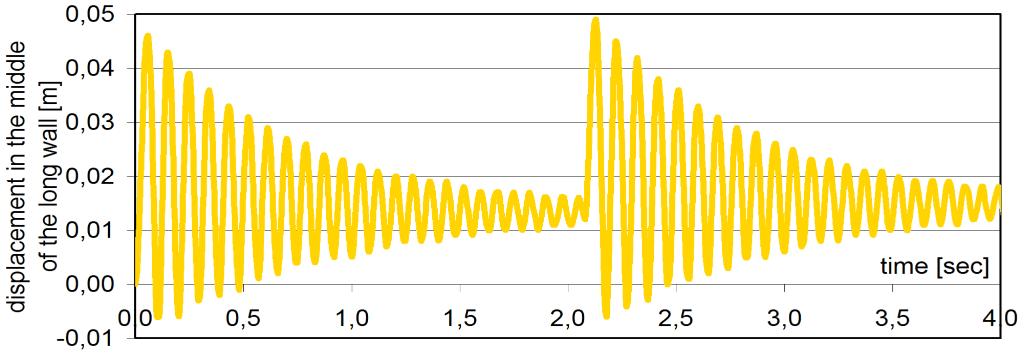


Fig. 9 Computed performance during the event of failure

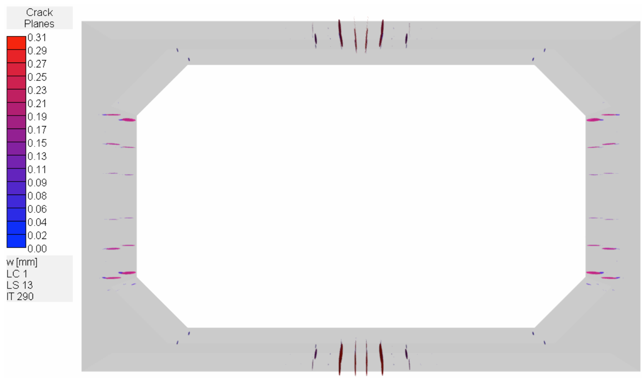


Fig. 10 Computed residual crack pattern


Fig. 11 Detail of damaged concrete containment

5 Conclusion

Fibre reinforced concrete was employed successfully for reducing the brittle failure mode of concrete and for increasing the ductility of the entire structure. The predictions of the event of failure and the observations after the event are in good agreement. This could be archived by performing an advanced nonlinear analysis and by the availability of mechanical parameters for fibre reinforced concrete. Further research is welcome in order to determine the crack closing coefficient β and the fracture energy of fibre reinforced concrete.

6 References

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