A Concept about Strengthening of Ship Side Structures Verified by Quasi-Static Collision Experiments

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ABSTRACT

The present work is dealing with the question, how to improve local parts of ship constructions to increase the safety of life at sea as well as environmental protection. Local parts which have to be strengthened are on the one hand selected parts of ship side structures and they are on the other hand constructions to protect tanks filled with highly explosive or flammable liquids like LNG. The strengthening is achieved by filling void spaces with granulate material. To investigate their effects on the failure mechanism, several quasi-static and large-scaled experiments were conducted on the test facility of TUHH.

KEYWORDS: *collision-test, side structure, strengthening, granulate material*

1. INTRODUCTION

This paper is based on a research work carried out in a collaborative joint research project. The project ELKOS started in 2009 and was finished in 2013. ELKOS stands for: „Improving collision safety by integrating effects of structural arrangements in damage stability calculations“. The scope of the project was divided in three sub-projects:

- validating collision calculations by large scale experiments using design variants of side structures
- development of a method to predict the damage stability of ship designs on the basis of the collision mechanics close to reality
- development of collision-mechanical analysis method for double-hull alternatives to identify damage calculation parameters

The superior research objective was to develop a method that allows adequate consideration of structural arrangements which significantly increase collision safety in damage stability calculations for new products. TUHH was engaged in this project with its institutes „Ship Structural Design and Analysis“- responsible for the first sub-project and „Ship Design and Ship Safety“- responsible for the second sub-project. The experimental structures were built at the German shipyard Flensburger Schiffbau-Gesellschaft (FSG) which was the industrial partner and also responsible for the third sub-project.

The Institute of Ship Design and Ship Safety determined the statistical distribution of the collision energy with a Monte-Carlo-Simulation. With this method the probability of the double hull failure of specific side structure constructions was predicted. The determined probability of the double hull failure corresponds well with the regulation of the SOLAS 2009 B1. For side structures which increase the collision resistance significantly the probability of the double hull failure was determined and could have been integrated in the damage calculation in form of a probability distribution. Thus the damage calculation index according to SOLAS 2009 B1 could be calculated. Thereby it was found that a side structure being locally improved to increase the collision resistance has a marginal influence on the leakage safety index. The reason therefore is based on the fact that the improved structures only prevent leakage of compartments for low-energy-collisions. The statistical part for low-energy-collision appears rarely for the examined RoRo-ferry. For that reason an economic benefit according to SOLAS 2009 B1 could not be realized. Finally the results show that it is not advantageous in respect of the leakage safety index to shift the inner hull towards the outer hull by realizing an equivalent absorption of energy regarding the SOLAS 2009 B1. For more details see Krüger et al. (2014).

However, the authors like to mention that in reality a lot of sailors lost their lives due to collisions in coastal areas. In the period of the years 2002-2012 sixty-six ship collisions were registered by the German Federal Bureau of Maritime Casualty Investigation (BSU). Most of them happened in the Kiel-Canal (12 cases), Port of Hamburg (10 cases), river Elbe (6 cases), river Weser (4 cases) and Kiel (3 cases). Thereby three sailors lost their lives in the Kiel-Canal and one sailor on the river Elbe. Furthermore the society's attitude towards environmental protection has changed severely during the last decades. The demand for safer transports of chemicals and fuels especially in coastal areas has become a very important matter with high priority. Thereby it is justified that also low-energy-collisions have to be investigated to prevent human lives and to avoid environmental damage.

In addition to this fact the authors note that the safety level of cars due to crash according to the European New Car Assessment Programme (EURO NCAP) is done for velocities of 29 km/h for side pole and 50 km/h for side mobile barrier and frontal impacts. Generating a speed range out of the EURO NCAP crash tests with an upper and a lower bound by taking a Cayenne (Porsche) and a Mini (BMW Group) the range of 13-27% can be determined. This range covers 3.2-5.5 kn regarding a large container ship (187 625 tdw, v_{max}=24.3 kn) and the range 2.9-4.9 kn for a smaller container ship (11 500 tdw , v_{max}= 18.3 kn). However, structural improvements for higher safety are restricted by physical bound. Up to this bound engineers have the possibility to work preventively and to evaluate this work. Furthermore, the authors present the results of the first sub-project for a reinforced side structure.

After several disasters of tank ships causing enormous environmental pollution due to oil spills, new IMO construction requirements for oil tankers had been established. These requirements are addressed to all tank ships ordered after 6 July 1993 had to be built with a double hull or an alternative design. The possibility of an alternative design poses a new challenge on engineers.

One obvious disadvantage of all presented structures is that they are very expensive in manufacturing and owners have to modify the common and approved structure. This leads to an additional risk in operation for example fatigue.

The idea of filling foamed material or concrete in void spaces of ship side structures is not new. The already realised designs served as additional safety in case of flooding regarding the hydrostatic of ships. At the beginning of the 20th century the double bottoms of lifeboats were filled with cork and in 1994/1995 the void spaces of the ferry SIER were packed with blocks of EPS, see Kulzep (2001). The first design of a 171.8 m long ship for the transport of radioactive waste was published in Hutchison (1987). This design was provided with blocks of urethane with a density of 101.9 kg/m^3 to increase the safety in case of a collision. Collision experiments with side structures equipped with filling material are not known.

The only known experiment related to collision experiments is published in Nagasawa et al. (1981) who investigated ship structures which struck a bridge pier. The aim was to protect the bridge pier. Therefore a composite-type consisting of outer hull and polyurethane filled inside and a grid-composite type also packed with polyurethane were investigated in collision experiments with a rigid bow model. Next to the already mentioned collision experiments in the Netherlands one grounding experiment was conducted, see Kulzep (2001). A double bottom structure was packed also with blocks of polystyrol with a density of 22 kg/m^3 and driven against a synthetic rock in a real grounding experiment.

Finally, a current draft International Code of Safety for Ships using Gases or other Low flashpoint Fuels (IGF Code) by IMO shows certain parallels to the construction requirements for tank ships in the future. In case of an external damage caused by collision the suggested regulation 5.3.4 demands that the fuel storage tanks shall be placed as close as possible to the centreline. Minimum is the lesser of B/5 and 11.5 m from the ship side at right angles to the centreline at the level of summer load line. In the IGF Code an alternative design is also in the discussion and moves a strengthened side structure in the focus of engineering.

Concluding all presented concepts one major disadvantage is that the steel-core or the filling material will make inspections for class renewal in periodical time difficult. For an alternative design to protect e.g. LNG storage tanks a potential filling material must be easy to remove and to refill after inspection.

2. EXPERIMENTAL CONDITIONS

2.1 Test model of the side structure

In two collision tests the protective effects of the investigated granulate material could have been determined. Hence a conventional side structure derived by a RoRo-vessel (designed and built on the German shipyard FSG) was scaled approximately 1:3 except the stiffeners and the frames. The conventional side structure was used for both experiments, except of minor modifications in applying different kinds of collar plates.

The complete test model has a length over all of 5788 mm, a breadth of 3490 mm and a height of 900 mm as presented in Figure 1. The investigated area within the surrounding support-constructions measured a length of 3400 mm and a breadth of 2260 mm. The wall thickness of the four web frames amounts to 5 mm and the two shell plates amount to 4 mm. The frames of the side structure consist of eight bulb profiles HP 140x7.

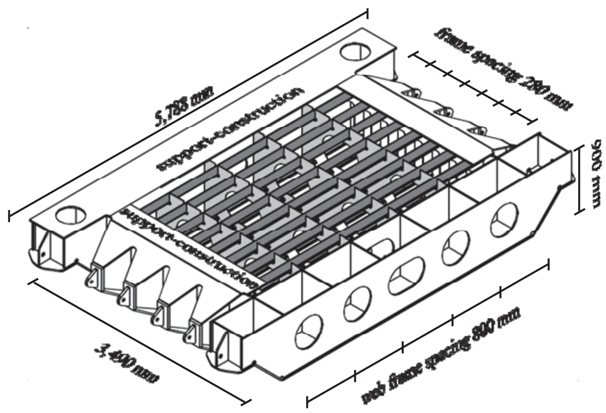

Figure 1 Side structure without shell plate

Both collision tests were enforced with a cylindrical rigid bulbous bow. The construction measured a diameter of 813 mm and a length over all of 1700 mm. The collision angle was 90°. With a collision speed of 0.2 mm/sec the whole test procedure is quasi-static, see Tautz et al. (2010).

2.2 Granulate material

For the determination of the granulate material following aspects were considered: Environmental harmlessness, hydrolyse and heat resistance as well as less mass density. The choice of an eligible material enables inspections of the structure.

Hence the filled side structure was equipped with multicellular hollow spheres made out of glass which exhibit the specification of Table 1.

Table 1 Specification of glass multicellular hollow spheres

grain size distribution	>2.0 mm
bulk density	190-250 kg/m^3
grain density	380-480 kg/m^3

This mineral material has the following useful characteristics: fire-proof, good thermal insulation, heat resistant up to ca. 900 °, hydrophobic, acoustical absorption, high adhesion, environmental friendly production and 100% recyclable. It is very light for granulate material, has good characteristics under compressive load and is easy to remove/ refill with the use of an industrial hover.

2.3 Test plant and configuration

Both collision tests are carried out on the existing test-plant of the Institute of Ship Structural Design and Analysis of TUHH, see Figure 2.

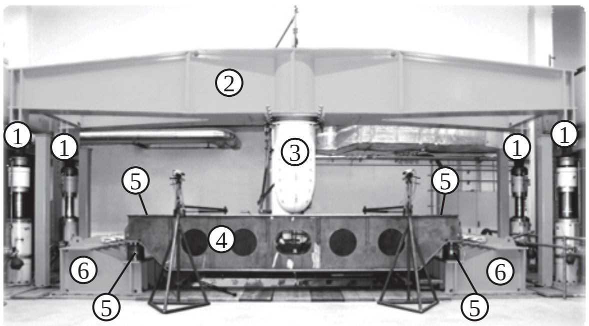

Figure 2 Test plant and configuration

Collision forces are applied by four hydraulic cylinders (1) which are connected with a cross-beam (2). The test model of the bulbous bow (3) is located underneath the middle of the cross-beam and is driven against the side structure (4).

Collision forces are measured at the hydraulic cylinders as well as at the pressure load cells (5) between side structure and support (6). The hydraulic cylinders are limited to 400 mm regarding the maximum range of displacement. Thus larger displacements are implemented by using appropriate interim pieces between the bulbous bow and the cross-beam.

2.4 Experimental results

In Figure 3 the measured results of both experiments are compared with each other. The measured results of the collision test with the conventional side structure are represented by the grey curve and the results of the collision test with the filled side structure by the black graph.

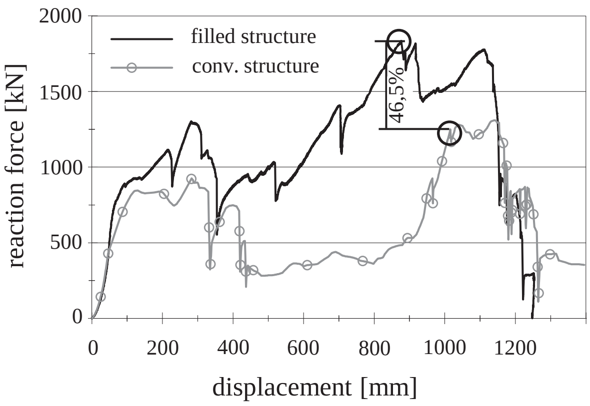

Figure 3 Measured reaction forces

The meaningful characteristics of the reaction forces are described in Schöttelndreyer et al. (2013). The cracks in the inner shell occur at the two marked points in Figure 3 and are chosen for comparison of the absorbed energy plotted in Figure 4. In total a significant increase of the reaction force of 46.5 % was achieved by the side structure filled with multicellular glass hollow spheres.

The integration of the reaction forces in Figure 3 leads to the absorbed energies of the side structures. The filled side structure has got the ability to absorb 70.5% more energy than the conventional side structure at the time of the inner hull failure.

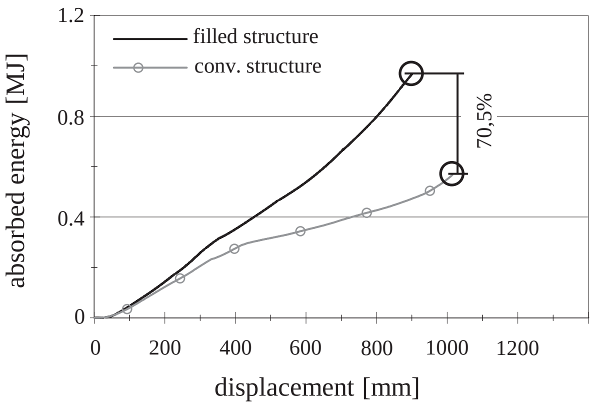

Figure 4 Absorbed energies of conventional and filled side structure

This significant enhancement of absorbed energy is generated by two effects. The primary effect is the compression and the collapse of the multicellular glass hollow spheres. At the beginning the material exhibits a crushable behaviour. Under high compression the material changes its constitutional characteristics and becomes a hard mass with a nearly incompressible behaviour. The secondary effect is the transfer of the reaction force to the inner hull construction which arises from the constitutional change of the multicellular glass hollow spheres of the primary effect.

3. VERFICATION OF SIMULATION

The properties of the steel structure were determined by numerous specimen in the form of tensile tests in accordance to the Norm DIN EN ISO 6892–1 (2009) and the choice of one numerical optimization tool as well as one validated power law hardening approach, see Schöttelndreyer (2015). For highly non-linear simulations a failure criteria must be determined which deletes finite elements by reaching e.g. a critical rupture strain. The criteria developed by Scharrer et al. (2002) in charge for the German classification society Germanischer Lloyd (since 2013: DNV GL) is quite simple in appliance and generates good results in simulations for ship collisions which was confirmed within the project ELKOS. The critical rupture strain ε_c represents the first principal strain and can be calculated for the uniaxial stress state by equation (1)

$$\varepsilon_c = 0.079 + 0.76\frac{t}{l_e} \tag{1}$$

and for the biaxial stress state by equation (2).

$$\varepsilon_c = 0.056 + 0.54\frac{t}{l_e} \tag{2}$$

The parameters t and l_e describe the shell thickness and the element length. To determine the properties of the multicellular glass hollow spheres several different tests had to be accomplished. The deviatoric perfect plastic yield function for the chosen material "Soil and Foam" developed by Krieg (1972) is given in equation (3):

$$\Phi = J_2 - \left(a_0 + a_1 \cdot p + a_2 \cdot p^2\right) \tag{3}$$

The parameter J_2 is the second invariant of the stress deviator and the constants a_0, a_1, a_2 characterise the deviatoric plane and must be calculated. The hydrostatic pressure p can be evaluated with the principal stresses measured in triaxial compression tests in accordance to the Norm DIN 18137 – 2 (2011) known in the geotechnical engineering to predict the behaviour of soils. The volumetric part of the yield function as well as the plastical deformability was achieved by using uniaxial compression tests. Further details are published in Schöttelndreyer et al. (2013).

3.1 Comparison between Experiment and Simulation

For all collision simulations the programme LS-DYNA version 971/ R6.1.0 is used. Therefore the geometry of the side structure was simplified. The stiffeners of the outer and inner hull are modelled with beam elements in order to avoid geometric disturbances for solid elements. They only have a different breadth but the same height and cross section like the bulb profiles. With this modification the granulate material could be modelled with five blocks of solid elements using a mapped mesh.

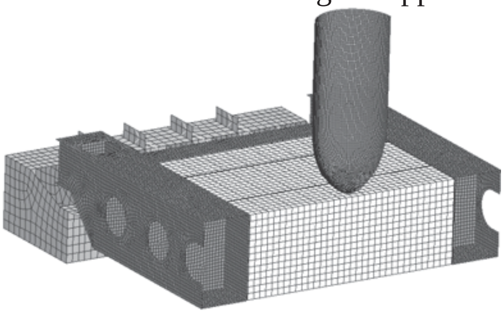

Figure 5 Half of the FE-model without outer shell

The outer and inner shell are modelled with four-noded quadrilateral shell elements using five integration points through their thickness and their critical rupture strain which is calculated by equation (2). Caused by the different scale rates for the stiffeners (more than 1:2), the equation (1) cannot be used for the test model of the side structure. In Schöttelndreyer et al. (2013) a critical rupture strain was determined by simulations. In Figure 6 the reaction forces of the experiment and the appendant simulation are presented.

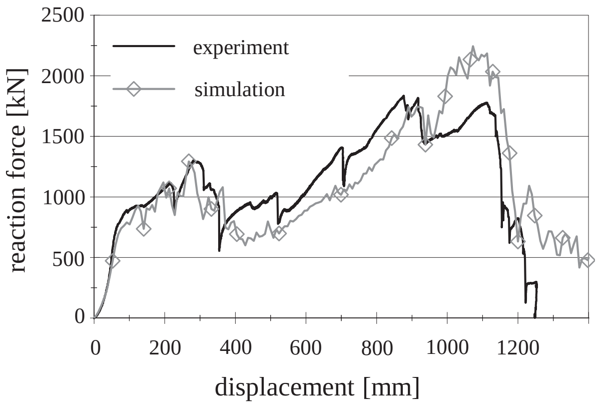

Figure 6 Comparison of the reaction forces

The simulation underestimates the reaction force with 5%. The displacement is 1% deeper as measured in the experiment when the first crack in the inner shell occurs. Only the failure of the frames is overestimated at a displacement between 1000 mm and 1200 mm.

Thus a transfer to real structures is justified and delivers furthermore conservative results.

4. NUMERICAL EXAMPLE OF USE

On 3rd of Mai 2013 a collision occurred between the ferries NILS HOLGERSSON and URD in the port of Lübeck-Travemünde. During a turning-manoeuvre the NILS HOLGERSSON struck the parallel middle body of the URD which was fastened to the pier. This collision leads to the structural damage of the URD above and underwater and to a minor damage of the bow structure. The damage of both vessels is shown in Figure 7.

Figure 7 Collision between the ferries NILS HOLGERSSON and URD in the port of Travemünde

Using the experience of this accident, the benefit of the granulate material in a real ship structure is quite simple to investigate. The dissipated energies as well as the ship motions are not difficult to calculate. Almost the whole kinetic energy of the NILS HOLGERSSON is dissipated by the structure of the URD. The kinetic energy can be determined with the known equation (4).

$$E_{kin} = \frac{1}{2}\Delta v^2 \tag{4}$$

The required data like displacement Δ, draft, trim of the NILS HOLGERSSON are published in the report of the Bundesstelle für Seeunfalluntersuchung (2013). All the other values like AIS-data, geometry of the NILS HOLGERSSON, main frame as well as several photos of the damage of the URD were given by diverse institutions.

The struck ferry URD was built in 1981 on the Italian shipyard Nuovi Cantieri Apuania. In 2001 the ship was extended with a 20.25 m long mid-part-section which was struck. She has got a length and a breadth over all of 171.05 m and 20.82 m and a maximal depth of 5.43 m. The design of the main frame with all characteristic dimensions is presented in Figure 8.

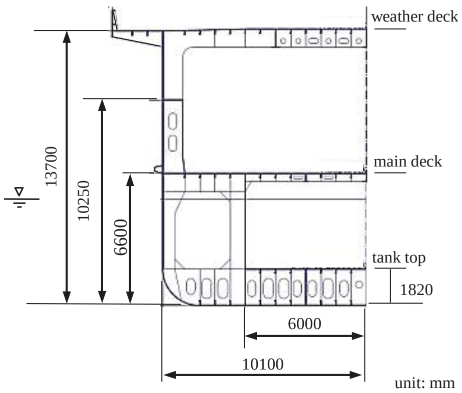

Figure 8 Main frame of the URD

The frame spacing and the arrangement of web plates are plotted in Figure 9 and amounts 750 mm and 1500/2250 mm.

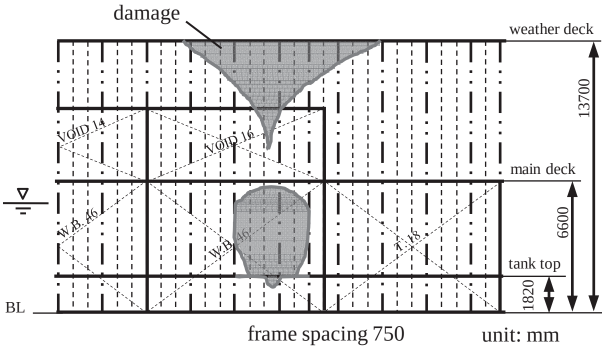

Figure 9 Side view (10100 mm) of the modelled section with the projected damage of the URD

The striking ferry NILS HOLGERSSON was built in 2001 on the German shipyard SSW Fähr-und Spezialschiffbau GmbH. She has got a length and a breadth over all of 190.77 m and 35.87 m and a maximal depth of 6.20 m. She struck the URD with a displacement of 20500 t in a collision angle of 82° with a speed of 6.52 kn. Caused by the minor damage her bow structure is discretised as a rigid part.

To confirm the benefit of the multicellular glass hollow spheres in the structure of the URD a FE-model validated by Martens (2014) is taken and modified analogical to the filled side structure model of the experiment. The size of the four-noded quadrilateral shell elements of the outer and inner shells amounts to 100 mm. In the model of Martens (2014) the stiffeners of the conventional structure are modelled as L- profiles with nearly the same section modulus like the original bulb profiles. Therefore the rapture strain is calculated by equation (2). Comparative simulations of the conventional structure with shell elements and beam elements for the stiffeners deliver comparable results. The rupture strain for the beam elements is determined by equation (1). The blocks of solid elements to describe the behaviour of the multicellular glass hollow spheres range from baseline to main deck and from inner hull (6000 mm) to outer hull (10100 mm), see Figure 8. The movement of the model is prohibited in all translational directions at mid ship and only in longitudinal direction of the ship at the two ends of the section. The rigid bow structure of the NILS HOLGERSSON is driven against the structure of the URD with the above mentioned velocity of 6.52 nm at the beginning of the simulation.

4.1 Benefit of the multicellular glass hollow spheres

For the evaluation of this analysis the calculated energies are separated in one part which is absorbed by the steel structure above the water surface and one part which is absorbed by the steel structure beneath the water surface. In order to realise further analysis of the filled structure, the granulate material is separated in addition. In Figure 10 the black curves represent the energies of the conventional structure and the grey curves of the filled structure.

Before the outer shell fails there is no benefit to observe in Figure 10. The outer shell fails in both simulations at a penetration of 3.5 m with almost the same energy level. At a penetration of 4.0 m the multicellular glass hollow spheres start to act.

The energy absorption of the underwater hull increases significant at a penetration of 4.5 m. Also in these simulations the two mentioned effects of the multicellular glass hollow spheres are confirmed. At the maximal penetration of 6.5 m in the simulation of the filled side structure the multicellular glass hollow spheres absorbed 24 MJ which is the primary effect. In addition 28 MJ are dissipated of the steel structure beneath the water surface. The steel structure beneath the water surface of the conventional side structure exhibits the absorption of 17 MJ at a penetration of 6.5 m. That demonstrates 11 MJ less than the structure of the filled model. This 11 MJ are dissipated because the collapsed multicellular glass hollow spheres also change their constitutional characteristics and become incompressible in a real ship structure. This behaviour enables the transfer of the collision force to a large area of the inner hull construction with its stiffeners and web frames. The stiffeners and web frames deflect the collision force to the main deck and tank top as well as to the bulkheads.

Using multicellular glass hollow spheres in the structure of the URD shows that the rupture of the inner hull could have been avoided and therefore the flooding of the investigated compartment would have been prevented.

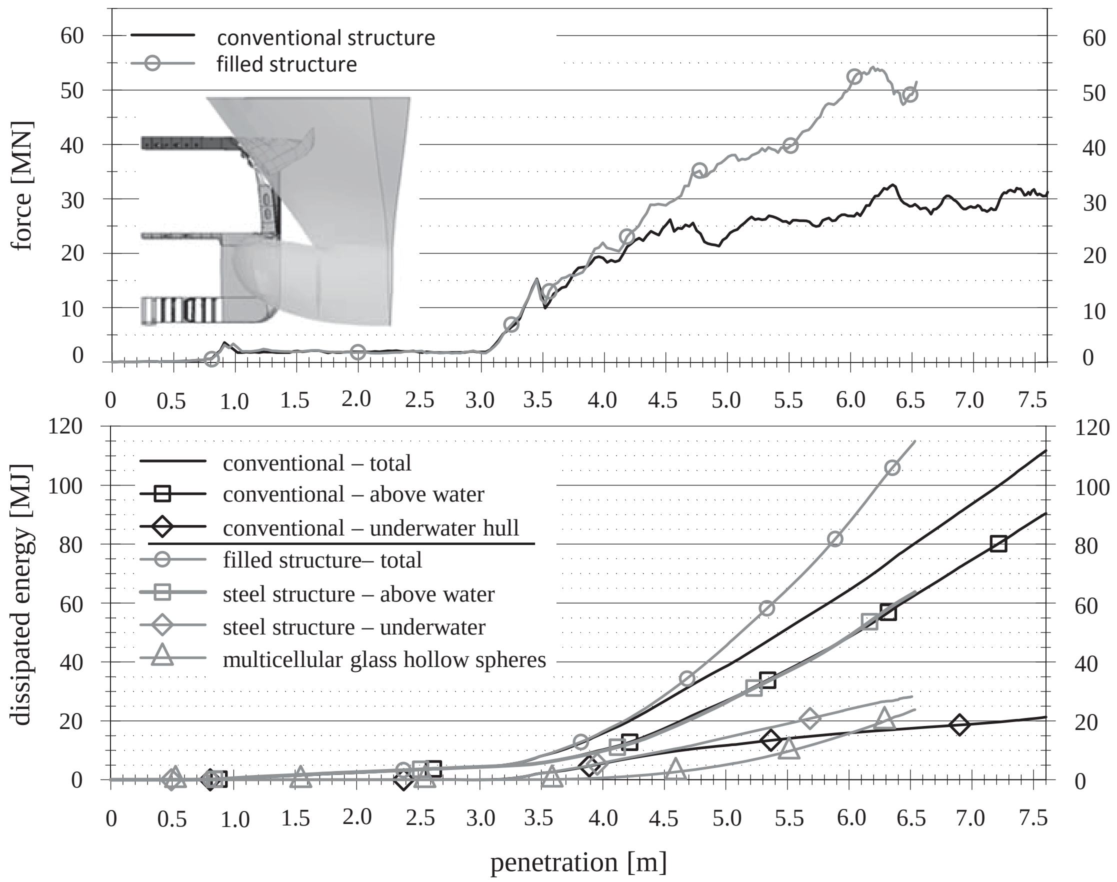

Figure 10 Results of simulation of the conventional and the filled side structure

4.2 Additional benefit of the multicellular glass hollow spheres

The determined benefit leads to the following question: What is the advantage for owners?

First at all they can protect their sailors/ goods with a strengthened ship structure and prevent environmental damage for low-energy-collision. In reality owners are still in a hard competition. Therefore they normally tend to comply with the existing regulations. If the regulations give benefits for safer and strengthened ships in future, owners will modify the structure of their existing ships or order new ships which will increase safety at sea.

Regarding the already introduced draft IGF Code with an estimated allowance of alternative designs, owners will have a justification for reducing the distance (less than B/5) between storage tanks and ship side which might increase the loading capacity of their cargo holds.

This advantage can be illustrated with a simulation where the inner hull of the ferry URD is shifted, see Figure 11.

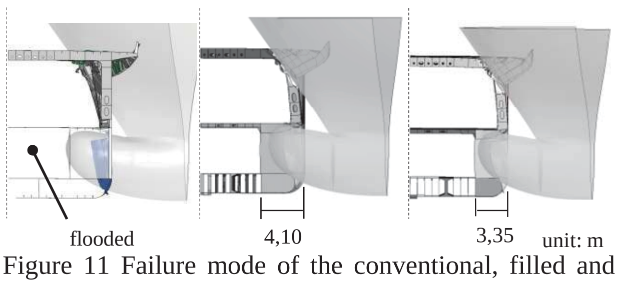

Figure 11 Failure mode of the conventional, filled and filled structure with shifted inner hull

Her double bottom construction is designed with longitudinal stiffeners with a spacing of 750 mm. In this simulation the inner hull of the URD is shifted one stiffener towards the outer shell and the void is filled with multicellular glass hollow spheres. Also with this arrangement the flooding of the compartment could have been avoided.

5. CONCLUSIONS

This paper presents a simple but extremely effective concept to strengthen ship side structure. The concept with a granulate material inside of void spaces enables inspections without complications in a periodical time. Therefore a conventional side structure and a side structure equipped with multicellular glass hollow spheres enhanced with a rigid bulbous bow were conducted. The results showed that the filled side structure absorbed 70.5% more energy than the conventional one. With the knowledge of the experiments and the appendant and validated simulations the protecting effects of the granulate materials can be transferred to real ship structures.

Therefore one collision scenario is chosen which happened on the German maritime waterways in Lübeck-Travemünde. Without regarding the SOLAS 2009 B1 the concept enables the possibility to strengthen the side structure according to the conventional design on the one hand and on the other hand to reduce the distance of inner hull and outer shell to get larger cargo holds which generates an economic benefit for the owners.

This gives designers more possibilities for modification of existing ships e.g. to protect a LNG power unit as well as for the general structure arrangement of new ships. This concept does not touch the conventional and approved construction and owners do not take an additional risk by using a new strengthened ship construction.

6. ACKNOWLEDMENTS

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