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MEC-E8007 Thin-Walled Structures

Lecture 12. Collision Strength and Crashworthiness Analysis

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The final topic is about crashworthiness which typically is also the last thing in design that we focus on thin-walled structures. The analysis contains a full understanding of non-linear material behaviour but also non-linear structural mechanics inclusing contacts. Thus you cannot learn this without knowning these aspects.

Contents

- The aim is to understand the methods to assess the collision strength of large complex structures using FEM
- Motivation
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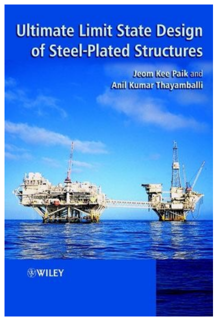
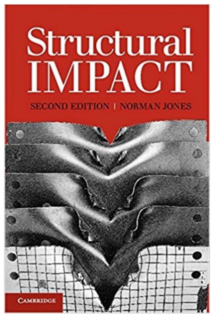
- Literature
  1. Jones, N., "Structural Impact", Cambridge Press
  2. Paik, J.K. and Thayamballi, A.K., "Ultimate Limit State Design of Steel-Plated Structures", Wiley

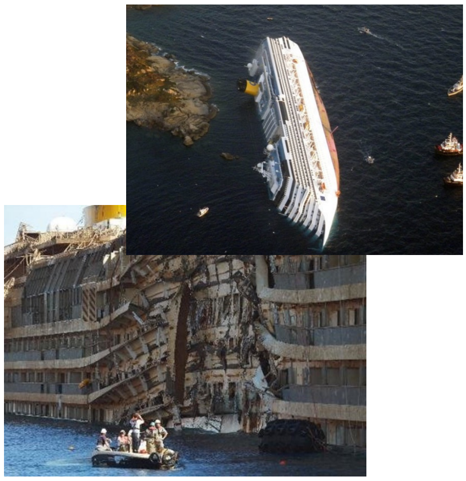


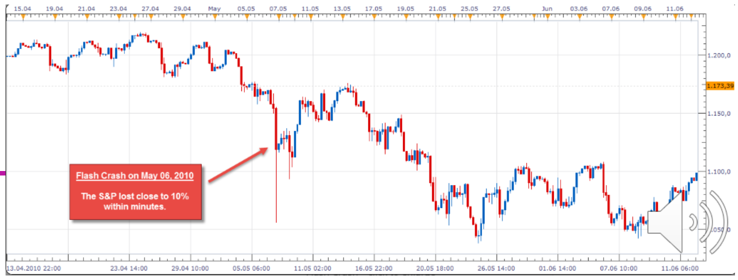


The aim is to understand the methods to assess the collision strength of large complex structures using FEM.

Motivation
Costa Concordia

- Thin-walled structures are often designed for normal operations where the extreme events (ultimate strength) and cumulative life time (fatigue) loading is known and/or can be monitored during operations
- Every now and then we experience “back swan” events which were not supposed to happen based on statistics or judgement
- Modern structural design accounts for these accidental events, e.g. collisions and groundings, explosions





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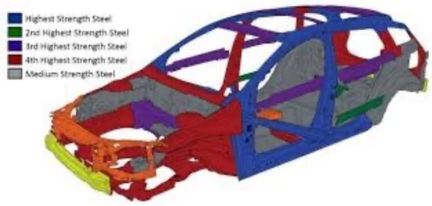
As a motivation, let’s have a look of the case we all know, the cae of Costa Concordia. Thin-walled structures are often designed for normal operations where the extreme events (ultimate strength) and cumulative life time (fatigue) loading is known and/or can be monitored during operations. Every now and then we experience “back swan” events which were not supposed to happen based on statistics or judgement of correct professional behavior. Modern structural design accounts for these accidental events, e.g. collisions and groundings, explosions at least to some degree.

Crashworthiness

- **Crashworthiness** is the ability of a structure to protect its occupants during an impact
- It is often assessed by experimental investigations to reach confidence on the actual performance
- Today computations are used to accelerate the design process and to make them more cost efficient (e.g., LS-DYNA, PAM-CRASH, MSC Dytran, Abaqus)
- Depending on the nature of the impact and the vehicle involved, different criteria are used to determine the crashworthiness of the structure
  - Water tightness
  - Accelerations
  - Penetration
  - Etc
- Key design parameter for thin-walled structure is the volume of the deforming material activated and plastic range of this material – this contributes to the energy absorbed



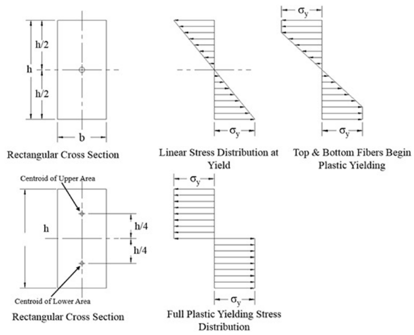
Crashworthiness is the ability of a structure to protect its occupants during an impact. It is often assessed by experimental investigations to reach confidence on the actual performance, while today computations are used to accelerate the design process and to make them more cost efficient (e.g., LS-DYNA, PAM-CRASH, MSC Dytran, Abaqus). In the end of the day we want to produce as good structures as possible and safety has been for a while a competitive factor for example in car industry. Chrashworthiness is also important for example in nuclear plants. Depending on the nature of the impact and the structure involved, different criteria are used to determine the crashworthiness of the structure, it can be water tightness, accelerations, penetrations and so on.
Key design parameter for thin-walled structure is the volume of the deforming material activated and plastic range of this material – this contributes to the energy absorbed.

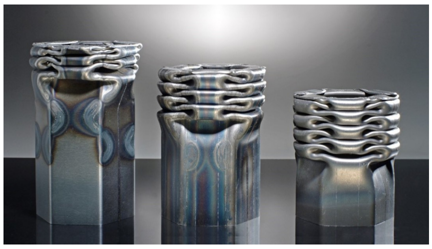
Crashworthiness

- The material can be activated by enabling large plastic deformations:
  - Membrane stretching
  - Plastic hinges
  - Friction between deformed structures
  - Fracture

- As important as the ductility of the material is the amount of material to be activated

- Therefore, we can have fold initiation points in our structures to maximise the energy absorption

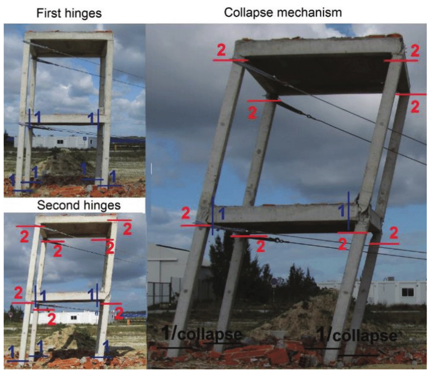




The material can be activated by enabling large plastic deformations in large volume, i.e. by membrane stretching and formation of controlled plastic hinges, friction between deformed structures and finally fracture which should be ductile to absorp more energy. As important as the ductility of the material is the amount of material to be activated and this is why we can have fold initiation points in our structures to maximise the energy absorption.

Crashworthiness

- The structure fails, when it becomes a mechanism
- In order to understand the failure we need to know:
  - The dynamic material behaviour (strain rates)
  - The material heterogeneity (welds, material interphase
  - Load carrying mechanisms and alternative load paths
  - Typical load situations
  - Etc
- We need to design our structures accounting these features… and for the black swans in these



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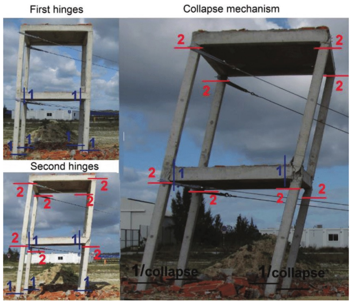
The structure fails, when it becomes a mechanism which means that it is not doing what it is designed to do. In order to understand the failure we need to know the dynamic material behaviour (strain rates), the material heterogeneity (welds, material interfaces), load carrying mechanisms and alternative load paths during failure and typical load situations in accidents among other things. We need to design our structures accounting these features… and for the black swans in these. This is why experience and learning from mistakes is essential part of the structural analysis.

Crashworthiness and assumptions
Experiments are needed…



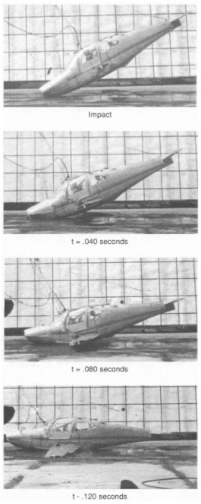


Figure 11. Crash Sequence, Test 4

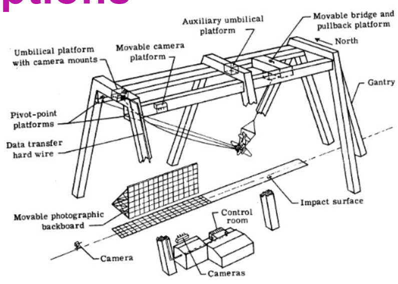
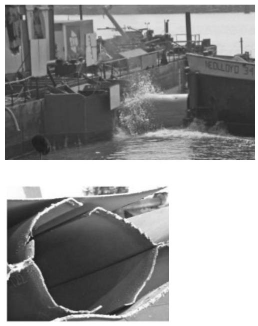
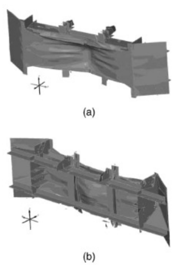


Figure 5. Diagram of NASA Impact Dynamics Research Facility





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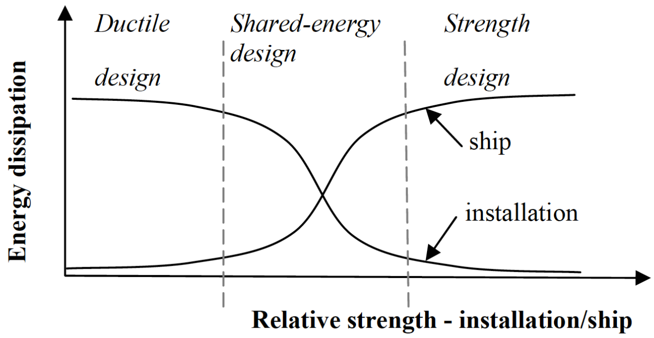
So in order to do proper designs, we need experiments so that we can learn from these, understand the role of our assumptions and how valid they are on to find really the energy levels which can be obtained from these structures.

Design principle and possibilities for repair



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When we talk about the design, we should think about the design philosophy for crashworthiness. Is it the colliding object or the one being hit in collisions that deforms? Can we fix the damaged structure and if so, where and when? This is why we may have ductile design in which the object we focus on takes the energy or strength design where the other object takes the energy. In between we have the shared energy design.

Internal mechanics versus external dynamics

- The analysis of collision interaction can be split into two parts:
  - external dynamics and internal mechanics
- Those two parts are often studied separately and linked together by the common contact force. The contact force can be controlled by structural design.
- Internal mechanics are used to evaluate the collision force as a function of penetration.
- Based on that curve and the collision scenario the motions and the extent of the deformation can be evaluated by external dynamics.

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The analysis of collision interaction can be split into two parts, one about the external dynamics and the other about the internal mechanics. Those two parts are often studied separately and linked together by the common contact force. The contact force can be controlled by structural design. Internal mechanics are used to evaluate the collision force as a function of penetration. This means the stress resultants, which are caused by non-linear materials and structural responses. Based on that curve and the collision scenario the possible motions and the extent of the deformation can be evaluated by external dynamics.

Example: Ship Collisions

- Colliding ships experience contact load resulting from the impact between the striking ship and the struck ship
- This force induces ship motions, which in turn cause forces exerted by the surrounding water
- While the striking ship is often handled as a rigid body, struck ship motions consist of rigid body motions and vibratory response of the hull girder
- Furthermore, in the presence of partially filled fluid tanks, the ship motions are affected by sloshing forces arising from the wave action at the free surface
- Usually the material behaves as ductile, but if the opening size increases dramatically the final fracture can be brittle

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Large–scale experiments

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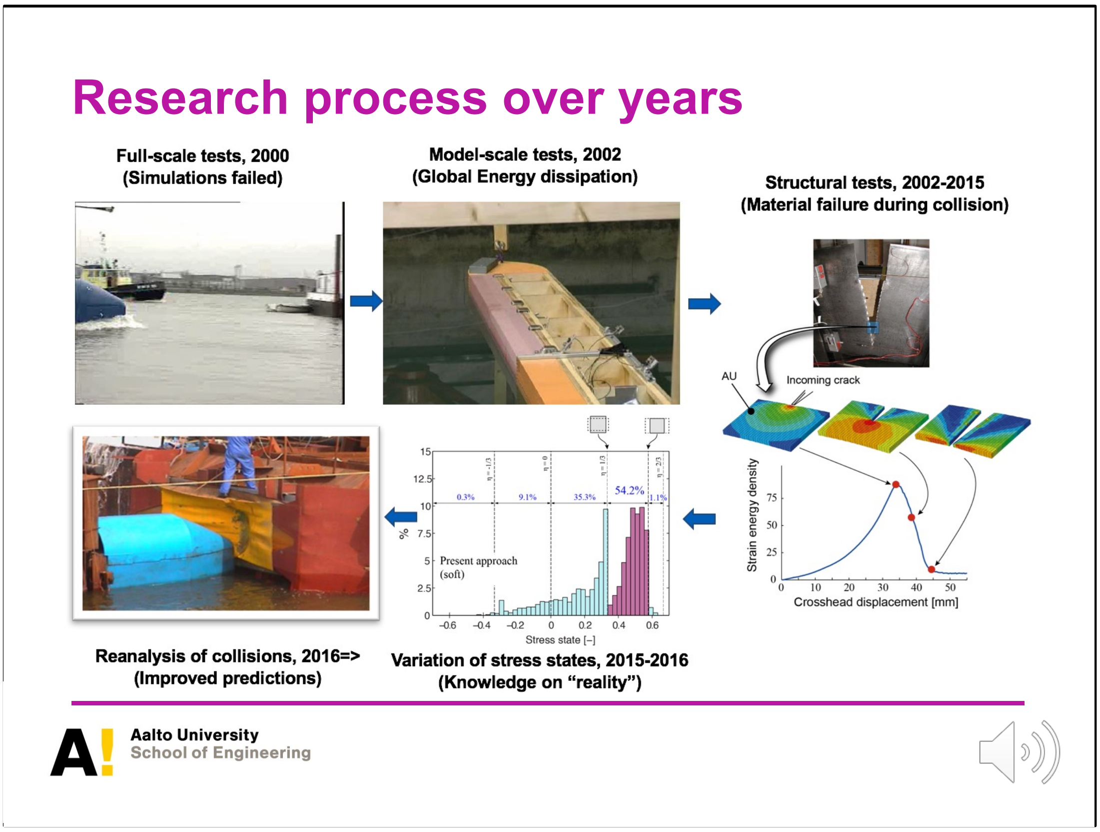
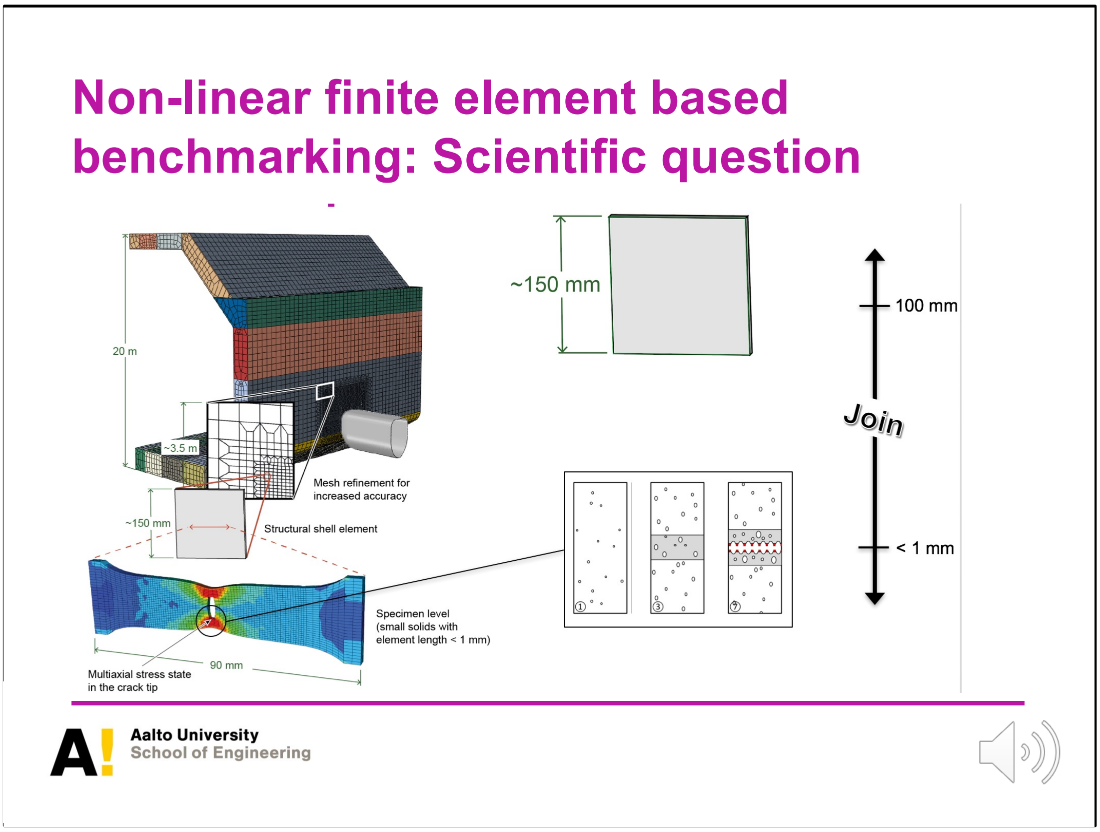
One possible scenario under controlled environment. However, this was performed in 1998, so you can imagine this is not everyday design practice to make tests with such large structure.

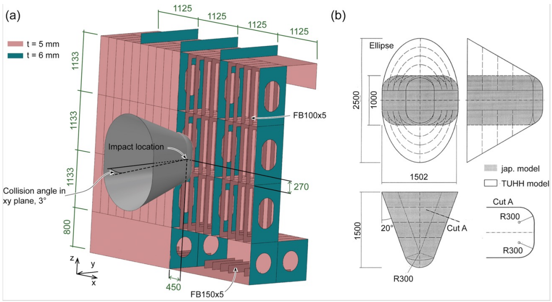


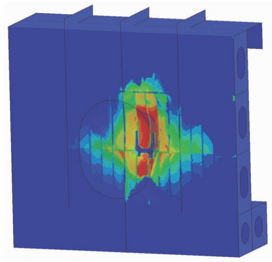
Here is an example of the research performed over the years. Full-scale tests were done based on numerical tools developed at structural and solid mechanics community for idealized load and structural model assumptions. The experiments did not agree with the simulations done by the best in business. In order to see the possible reasons for contact force, a series of model-scale experiments were done. At the same time material models were investigated more. We learned that the tanks, when being partially filled, contribute to the combined dynamics in unexpected way. We also learned that the materials behave under much more complex loading in complex thin-walled structures than the basic material experiments predict. We stated to reformulate the assumptions to get better agreement with the experiments.

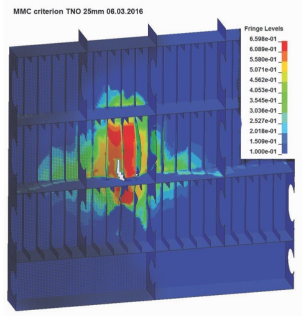


One issue is really the complexitity to the material modeling. In large structures, even if the contact force increases monotonically, the material may not see proportional load paths. Thus, the length-scale interaction is very difficult in space and time affecting the details of our solution significantly and in very complex manner.

Simulation of experiment







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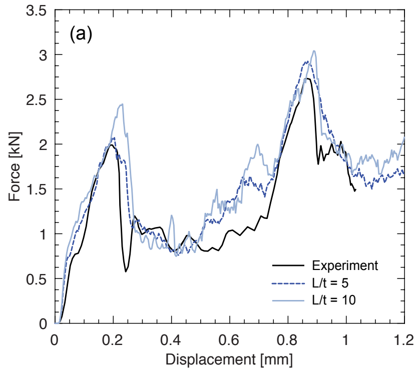
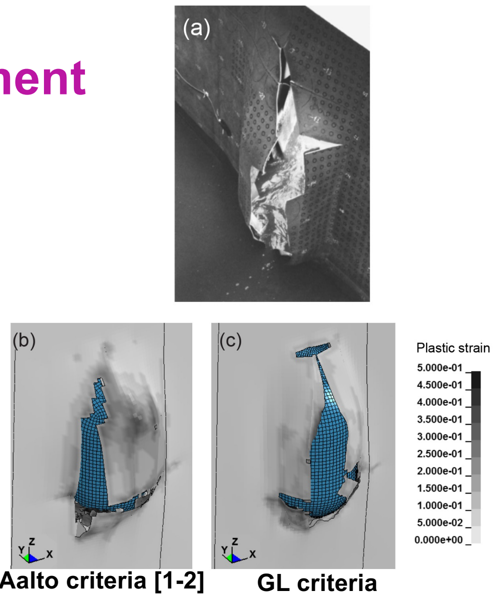
Here is an example of reduced model in which we consider the internal mechanics only and therefore, we can restrict the computational model size so that the deformations at the edges of the model and very small. This accelerates the computations a lot, but also at the same time simplifies the analysis a lot as we do not have the role of motions to the energy calculations included.

Simulation vs experiment





[1] Kõrgesaar, M., Romanoff, J., 2014. Influence of mesh size, stress triaxiality and damage induced softening on ductile fracture of large-scale shell structures. Mar. Struct. 38, 1–17.
[2] Kõrgesaar, M., Kujala, P., 2016. Experimental validation of failure criterion for large complex shell structures, in:. Presented at the International Conference of Collision and Grounding of Ships and Offshore Structures, pp. 1–7.

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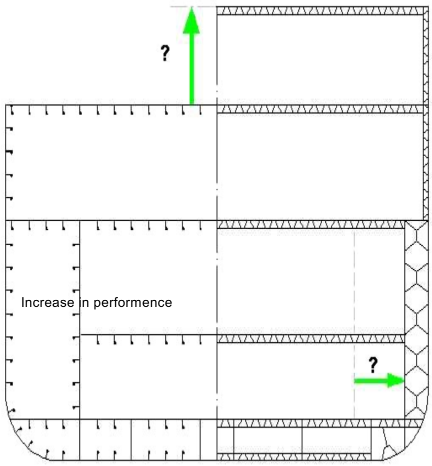
What you can see here is that the predicted result is dependent both on the element size ad also on the strength criteria you use for the material. Both the force displacement curve will change its shape but also the predicted opening size and shape will be different. What we do in practice is that we aim to secure that the shapes are correct, but also that the absorbed energy is equal between simulations and experiments.

Design of crashworthy ship

- Subject is either
  - crashworthy structure and/or
  - the whole ship concept.
- Enlarge the structural design scope from operational loads to accidental loads



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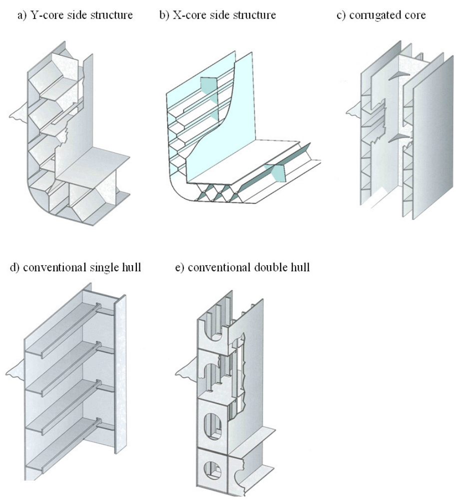
In order to design a crashworthy structure we must first think if we are making a strong plate or modify the entire ship concept. What you can see from the figure is that the left side uses the collision zone which affects the volume of the cargo hold negatively, while on the crashworthy side also the cargo volume increases with the crashworthiness. This type of thinking allows us to enlarge the structural design scope from operational loads towards accidental loads, which of course makes our structures more advanced but also requires from the designer more competence.

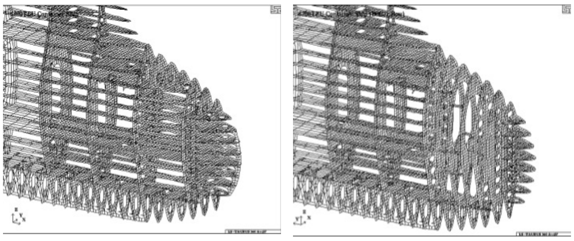
Increased damage tolerance by making structures softer?

- The main aim is to prevent flooding or oil out-flow
- Fracture delayed by avoiding structural hard points and increasing the number of plastic hinges



Introduction of a new design criteria is a challenge as increased damage tolerance means often that we are making structures softer. This is as the main aim is to prevent flooding or oil out-flow and to keep the structure fracture free as long as possible. In practice, the fracture can be delayed by avoiding structural hard points and increasing the number of plastic hinges in the deforming structure. This is why we use structures with multiple, slender and inclined surfaces. While the multiple and slender surfaces cause plates to fold and this way making more plastic hinges to absorb energy, the inclination makes the plates to fold at low levels and this way making them softer.

Means to decrease damage



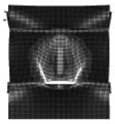
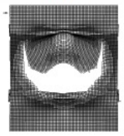
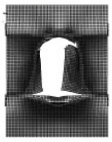
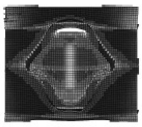
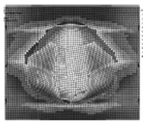
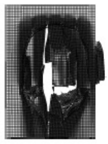
Buffer Bow Design for the Improved Safety of Ships Kitamura (V), Nagasaki R&D Center, Mitsubishi Heavy Industries, Ltd., Japan

Ulstein wave piercing X-bow
- Focus on comfort
- Added benefit of better load distribution during impact

The buffer bow design for the improved safety of ships was designed to absorb the loading with the colliding ship, this way taking the responsibility of safety away from the “victim” structure. On the other hand the X-bow concept was developed to have multiple purposes from the wave motions to the benefit of better load distribution during impact. Thus, when adding the new design criteria, we must look for solution that covers multiple design viewpoints.

Non-linear finite element based benchmarking

- Comparative fracture propagation plots

Test/Criteria	GLF	PES	RTCL
Test 1 penetration 0.75 m			
Test 2 penetration 0.75 m			
Test 3 penetration 1 m			

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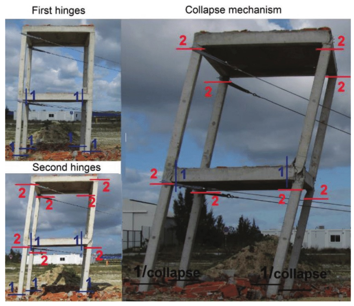
Part of the research is to learn what kind of implications do the different modeling strategies have to the outcomes of the simulations. Here we see an example of the same case being simulated for different initial conditions at up to different levels of penetration. What we can see from here is that the predicted opening sizes are very different and this can be crucial in other parts of design, for example here on the collision damage consequence assessment.

Summary

- Crashworthiness is one format of ultimate strength analysis where the aim is to maximise the capability of structure to absorb energy
- It is often assessed by experimental investigations to reach confidence on the actual performance
- Today computations are used to accelerate the design process and to make them more cost efficient (e.g., LS-DYNA, PAM-CRASH, MSC Dytran, Abaqus)
- Depending on the nature of the impact and the vehicle involved, different criteria are used to determine the crashworthiness of the structure
  - Water tightness
  - Accelerations
  - Penetration
  - Etc
- Key design parameter for thin-walled structure is the volume of the deforming material activated and plastic range of this material – this contributes to the energy absorbed



Crashworthiness is one format of ultimate strength analysis where the aim is to maximise the capability of structure to absorb energy in cases where the loading is unpredictable. That is, it is against the planned operations.

Crashworthiness is often assessed by experimental investigations to reach confidence on the actual performance and this is expensive on lare thin-walled structures. Due to this today computations are used to accelerate the design process and to make them more cost efficient with seveseral codes being able to do the required simulation tasks (e.g., LS-DYNA, PAM-CRASH, MSC Dytran, Abaqus).

Depending on the nature of the impact and the vehicle involved, different failure criteria are used to determine the crashworthiness of the structure: water tightness in ships, accelerations in satelites with high tech sensors, penetration in nuclear plants just to name a few examples of the system functionality affecting the assement.

Key design parameter for thin-walled structure is the volume of the deforming material activated and plastic range of this material – this contributes to the energy absorbed.