Effect of weld modelling on crashworthiness optimization

M. Kõrgesaar
Tallinn University of Technology, Estonian Maritime Academy, Estonia
J. Romanoff
Aalto University, Department of Mechanical Engineering, Finland
L. St-Pierre
Aalto University, Department of Mechanical Engineering, Finland
P. Varsta
Aalto University, Department of Mechanical Engineering, Finland

ABSTRACT: Design of ship structures that can absorb more energy during accidental loading scenarios without rupture contribute to the safety at sea. Therefore, innovative structural solutions have been sought for and implemented in practice, which have better crashworthiness properties compared with traditional stiffened panels. The enhanced characteristics are achieved through structural topology changes that lead to better energy absorption characteristics. To find the topologies with the best characteristics, optimization algorithms are commonly used. In this paper, we explore how these "best" designs are affected by the assumption made in modelling the structural joints such as welds and heat-affected zone. Web-core steel sandwich panels are optimized for maximum energy per mass (E/M) ratio until fixed penetration depth. Two alternative modelling techniques are compared, one where welds are considered and the other without welds. The differences in response and resulting best designs are discussed and presented.

1 INTRODUCTION

Design of ship structures that can absorb more energy during accidental loading scenarios without rupture contribute to the survivability of ship and thus, to safety at sea. Therefore, innovative structural solutions have been proposed (Hogström and Ringsberg, 2013; Klanac et al., 2009, 2005; Kõrgesaar and Ehlers, 2010; Naar et al., 2002; Rubino et al., 2008; St-Pierre et al., 2015), manufactured and tested in full scale (EU-project CRASHCOASTER, 2000-2004 and EU-project SANDWICH, 2000-2004), which have better crashworthiness properties compared with traditional stiffened panels. These enhanced characteristics are achieved through structural topology changes that lead to better energy absorption characteristics. One type of structural configuration is a steel sandwich panel. These panels have been extensively explored for crashworthiness enhancement and damage mitigation, whether as a potential novel solution for a ship side and bottom to mitigate damage, or as an effective deck structure that can sustain loads from dropped objects. While the potential of these panels have been amply demonstrated, the effect of joining methods and welds on the behaviour of panels is less documented.

The simplest core geometry of all-metal sandwich structures shown in Figure 1 is built from flat web-plates perpendicular to the face plates. The analysis presented in this paper is based on the experiments performed with such laser welded web-core steel panels that were quasi-statically tested in Aalto University (Finland). Experiments involved penetrating the sandwich and stiffened panels with rigid indenter until rupture and characterizing the mechanical response of ruptured material with different kind of tensile tests (Kõrgesaar et al., 2018b, 2018a, 2017). This experimental-numerical study indicated that weld modelling approach affects the numerically predicted response in sandwich panels (see Figure 2), while stiffened panel response could be adequately captured using different element sizes without explicit consideration of welds. One explanation for this is different load carrying mechanism between panels. Sandwich panel carried load with only few unit cells while stiffened panel with the entire structure. Post-experimental pictures of deformed panels in Figure 3 (a,b) show the differences in fracture path. Fracture in sandwich panel (Figure 3a) propagated along the heat affected zone (HAZ) and resulted in a straight path, while in stiffened panel circular path was formed (Figure 3b). Due to this fracture the “sandwich effect” have been lost as the shear transfer disappears.

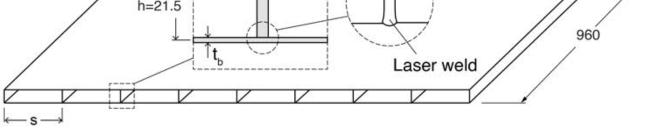

Figure 1. Web-core steel sandwich panel analyzed in this study. Picture adapted from (Romanoff and Klanac, 2007).

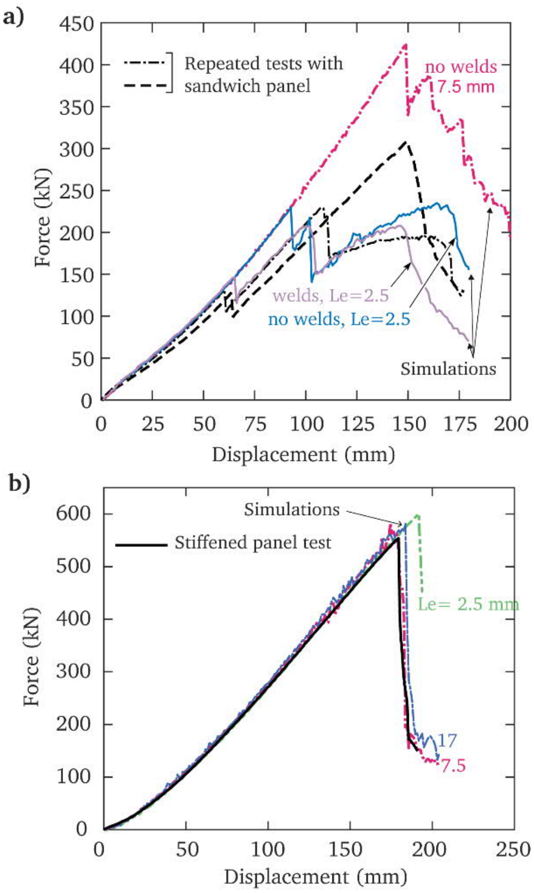

Figure 2. Experimental and numerical force-displacement curves. (a) Webcore sandwich panel. Effect of HAZ and change in element length L_e. (b) Stiffened panel. For variation of element lengths good correlation between simulations and experiment is obtained.

The effect of laser weld failure strain on the simulation of X-core sandwich structure was also investigated by Ehlers et al. (2012) by varying the weld failure strain value from 0.001 to infinity. For this range of weld properties, X-core structural response was not particularly sensitive, although welds definitely failed during experiments as indicated in the photograph in Figure 3(c). However, they did not consider the case where welds are not modelled at all nor did they account the changing material properties in the heat affected zone. On the other hand, insensitivity to weld failure strain could be explained by relatively soft core of the X-core structure that reduces the stress concentration at the HAZ.

One way or another, it is clear that laser welding changes the local material properties, but whether these changes should be considered in the design process remains questionable. Fundamentally, is the change in structural response so large that there is sufficient merit to model welds in simulations? To answer this question, we optimize the web-core panel for crashworthiness using two alternative approaches: the one where welds are modelled and other where they are not. The problem is setup in the optimization framework to mimic the actual design situation where the best designs are first mapped using numerical simulations. This is presented next.

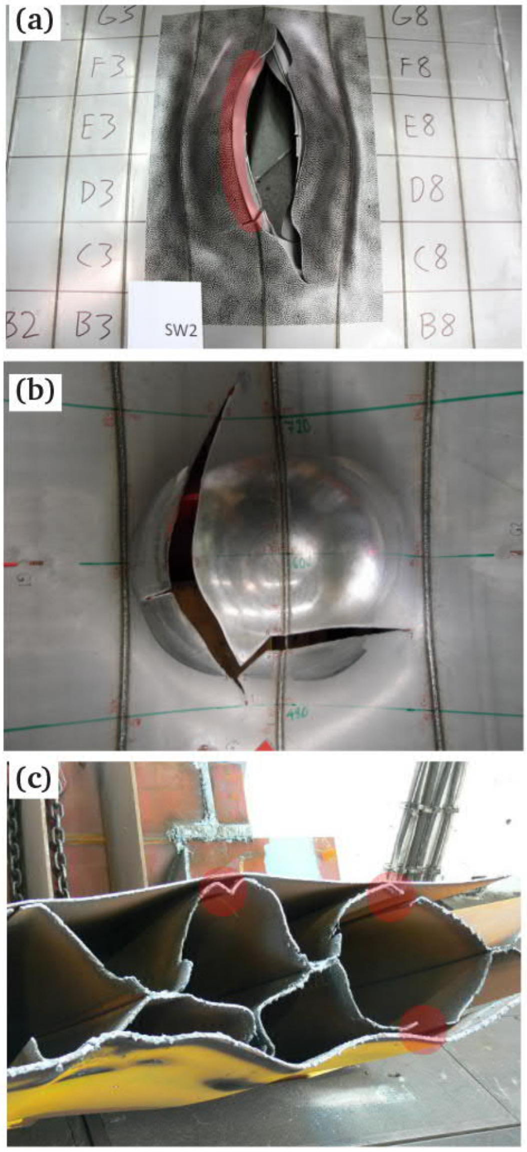

Figure 3. Failure in laser welded panels. (a) Web-core panel tested in Aalto with failure at HAZ (Kõrgesaar et al., 2018a). (b) Stiffened panel tested in Aalto (Kõrgesaar et al., 2017). (c) X-core panel tested as part of the EU Crashcoaster project (Wolf, 2003).

2 METHOD

2.1 *Numerical model*

The 'seed' model shown in Figure 4 is based on the details given in (Kõrgesaar et al., 2018a) where the numerical simulations have been validated by experiments. It included a deformable panel and rigid indenter. The panel was fixed by restraining all the displacement degrees of freedom (DOF) at the nodes at the outer boundary of the panel. Indenter could translate along z-direction, rest of the DOF were fixed. Two principal indenter positions (penetration locations) were considered to account for the average response of the panel:

- Position on the web location denoted as Pweb with an imperfection of 4 mm (see Figure 4). The imperfection reduces the probability that any numerical issues arise during optimization and thus increases the robustness of optimization.

- Position between the two webs denoted as Pface.

The impact between panel and indenter was simulated by assigning a constant vertical velocity (10 mm/min) to indenter. To speed up the simulations mass of the entire model was scaled by a factor of 10^7. Contact between different objects was modelled with general contact algorithm by defining rigid objects as masters. Contact definition included model for tangential and normal behavior. Tangential behavior between surfaces was modelled with penalty type friction formulation with friction coefficient of 0.23. Contact behavior normal to surfaces was modelled with "hard" pressure-overclosure relationship.

Model was meshed with reduced integration shell elements (S4R) with default hourglass control and 5 through thickness integration points. The mesh was graded so that fine mesh (~2.5 mm under indenter) coarsened away from the penetration zone (~15 mm). A strip of structured rectangular elements (2.5×2.5 mm) was specified in face plate and web interface that represented a zone of material affected by welding. In this zone, material properties had two alternatives:

1) First, the properties were the same as in the rest of the face plates. This modeling approach is denoted as **noHAZ.**

2) Second, the properties characteristic to heat affected zone determined numerically by Kõrgesaar et al. (2018a) were used. In other words, material had a higher yield stress than the surrounding base material and a constant equivalent plastic failure strain of 0.15. This modeling approach is denoted as **HAZ.**

These HAZ elements were defined only along face plate, but not on web. Furthermore, only single web-face interface closest to indenter tip was modelled like this. In the neighboring interfaces the mesh was not structured and base material properties were used. This eased the parametric modelling effort and is justified by experimental and numerical analysis. Namely, once fracture initiated in the HAZ at one interface, propagation continued along the same interface (Figure 3a). The reason is strong stress concentration at the weld location (Kõrgesaar et al., 2018a (Fig.12); Romanoff et al., 2007 (Fig10)). However, since experiments were performed with panels where web spacing was 120 mm, the uncertainty definitely exists for panels evaluated during optimization that have shorter web spacing.

Material was modelled with von Mises plasticity. Stress strain curves for both weld and base material are shown in Figure 5. These are based on the calibration in Kõrgesaar et al. (2018a). Fracture in base material was modelled according to stress triaxiality and element size (*Le/t*, element length to thickness ratio) dependent fracture criterion given (Kõrgesaar et al., 2018b, 2018a). Average failure strain value in base material in simulations was 0.5. The above described FE model generation was made automatic using Abaqus 6.14-1 Python based scripting language.

2.2 *Optimization*

The objective of the study is to determine how numerical weld modelling affects the topology of optimized designs in limit state situation where fracture has taken place. Design task is to find structural configurations that are lightweight, but effective in dissipating the deformation energy. In literature, such designs are often denoted as crashworthy designs and quantitatively described with Energy per Mass (U/M) ratio (Sun et al., 2018). Therefore, objective of the optimization was to maximize the plastic dissipation energy (U) divided by the structural mass (M).

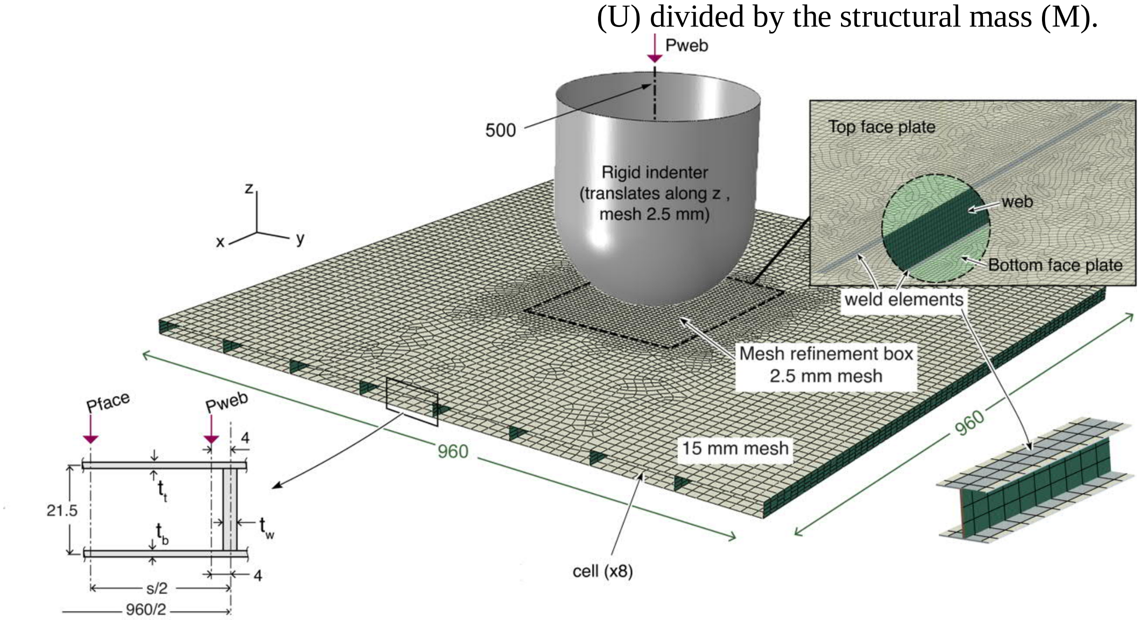

Figure 4. Numerical model setup.

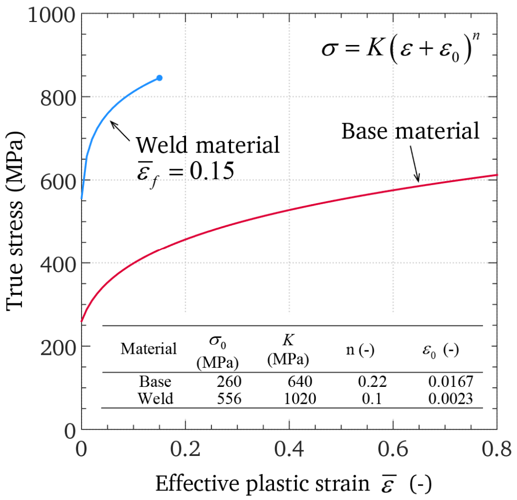

Figure 5. Material curves used in simulations.

Table 1. Optimization variables and PSO parameters

Variable	Range	step
tweb	1-10	1 mm
Tbottom	1-10	1 mm
ttop	1-10	1 mm
Cells	4-24	1
PSO parameters	Value	
Swarm size	10	
Number of generations	60	
Inertia at start	1.4	
Dynamic inertia reduction factor	0.8	
Number of rounds to improve solutions before the inertia is reduced	3	

To account for the average response of the panel energy was averaged between position 1 and position 2, which means that two simulation runs were performed with the same panel geometry.

The PSO algorithm implementation is based on Jalkanen (2006). Here, initial swarm had a size of 10. This small number is justified by the relative simplicity (in purpose) of the optimization problem. The solution space was explored using discrete design variables given in Table 1 and shown in Figure 4. Although PSO is inherently continuous, discrete design variables can be taken into account simply by rounding each design variable to closest allowed value, Jalkanen (2006). The only topological variation in the panel design was number of cells. Rest of the optimization variables were the top face plate thickness (t_t), bottom face plate thickness (t_b) and web plate thickness (t_w). The height of the panel h was kept constant at 21.5 mm in order to allow later experimental validation of the conclusions. The problem was set-up as constrained optimization meaning that all panels had to comply with the maximum allowed mass requirement. This mass was calculated for the 8 core panel (as in the seed geometry) with all constituents having 5 mm thickness. The uniform 5 mm plate thickness was preferred over original tested panel dimensions of 3-1.5-3 mm configuration in order to expand the design space. Mass was calculated as

$$M = \left[\left(s\left(t_t + t_b\right) + t_w h\right)\cdot cells + t_w h\right]\cdot L\cdot \rho \qquad (1)$$

where L=0.96 m is the panel length and $\rho = 7850$ kg/m^3 is the steel density.

3 RESULTS

3.1 *Optimization results*

Optimization results are shown in Figure 6. In Figure 6(a), the results are shown for penetration depth D of 180 mm (~8 × h_{panel}) for two modelling approaches, with and without simplified heat affected zone (HAZ), respectively. For both modelling approaches, the best designs in terms of U/M ratio are given: when HAZ is not modelled (denoted as noHAZ), U/M = 1.55 and when HAZ is modelled (denoted as HAZ) U/M = 1.38. Recall, that objective in optimization was to increase the U/M ratio since the higher ratio means better design in terms of crashworthiness. Figure 6 (b) seems to suggest that convergence was found in both optimization rounds. Comparison of obtained best designs with two modelling approaches shows that noHAZ technique, or exclusion of welds in simulation, leads to 11% higher U/M ratio. This discrepancy could be considered negligible if the best obtained designs, with and without HAZ, would be similar. However, Figure 6 (c) shows that designs are different. The greatest difference is in the web distance. In HAZ design web distance is maximized while in noHAZ design minimized. The thicknesses are more similar between models with face plate on the contact side being the thickest member, while rest of the plates have the minimum 1 mm thickness.

Deformation mechanics and final fracture morphology of both best designs are shown in Figure 7. Characteristically to crashworthy structure, section cuts of the noHAZ design indicate to more evenly distributed deformations compared to HAZ design, especially at the final stages. For each position the energy absorbed is brought out. There are notable differences in energy values for HAZ design. Much more energy is dissipated when indenter hits between two webs. Furthermore, in latter case fracture does not propagate to weld elements, i.e. elements with HAZ properties. That might explain convergence towards design that has the maximum web distance.

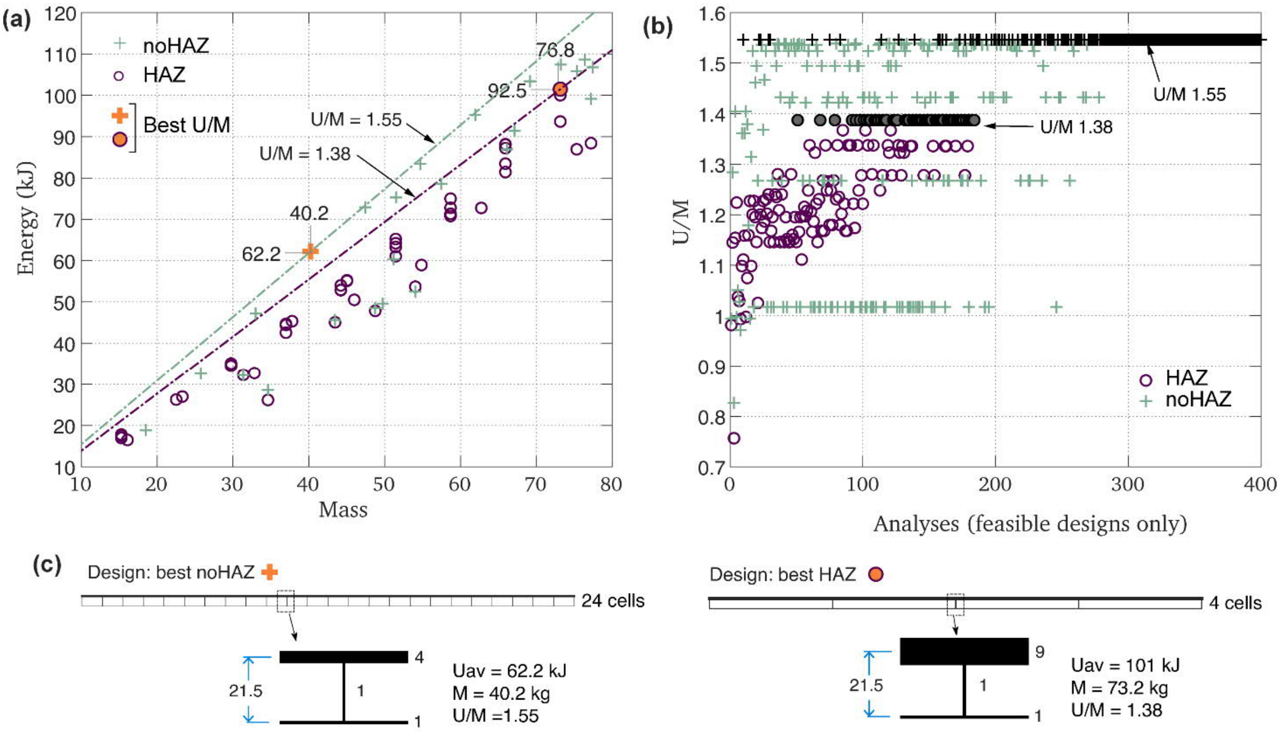

Figure 6. Optimization results. (a) Energy plotted as a function of mass for all design particles. (b) Convergence for both optimization runs. (c) Best designs obtained with different approaches.

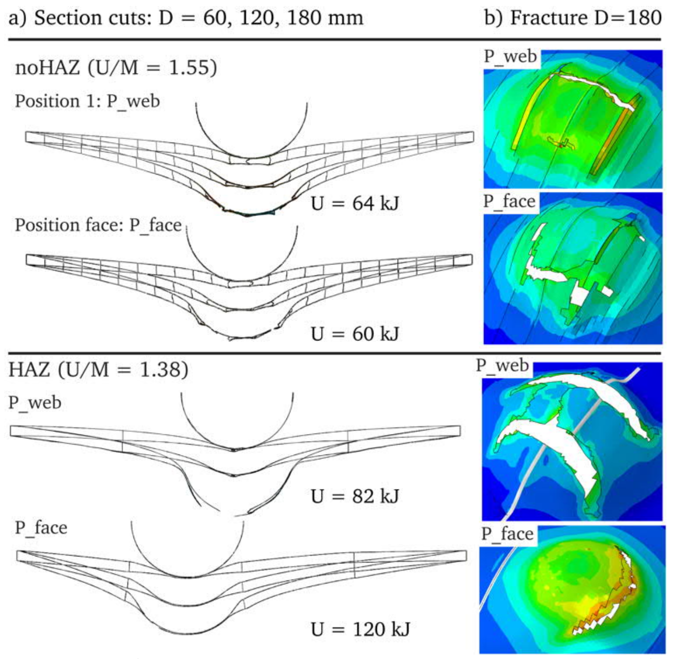

Figure 7. Deformation mechanics in best U/M ratio designs for both indentation positions. a) Sections cuts from the middle of the panel at three different penetration depths, 60, 120 and 180 mm. b) fracture pattern viewed from the bottom non-contact side (colour contours show the level of equivalent plastic strain).

The notion that optimization tends to converge towards a solution that minimizes fracture in weld elements is supported also by brief analysis of other HAZ design alternatives. In contrast to the fracture pattern in the best HAZ design where propagation has occurred across welds (Figure 7b), propagation in a design that had 3 mm bottom plate occurred along the weld similarly to tested panels shown in Figure 3(a). With that in mind, it is very important that fracture in the heat affected zone and in the base material is correctly predicted as otherwise preference of some designs would be unjustified. Recall that fracture in the base plate was modelled with fracture strain criterion that depended on the plate thickness, while in weld elements constant fixed fracture strain value was used. This uncertainty should be definitely addressed in future.

3.2 *Comparison of geometrically similar structures*

To further check the differences between the two modelling approaches and the hypothesis that optimization tries to avoid fracture in weld elements, we took the best noHAZ design geometry (Figure 6c) and used the HAZ modelling approach. There is also a practical reason for doing it this way, as opposed to using the best HAZ model geometry and modelling this without the weld elements. Namely, in a real design situation conventional noHAZ approach would be probably used for its simplicity. Including the welds in the model will in a way show uncertainty in the conventional approach.

Simulations were again done for two striking positions. Obtained force-displacement (F-D) and energy-displacement (E-D) curves for both modelling approaches are shown in Figure 8. For both loading positions, response is rather similar so average energy is shown. Adding welds to the simulation leads to 38% reduction in energy compared with simulation without welds. When the noHAZ design had the U/M ratio of 1.55, then HAZ design has U/M = 38.75 / 40.2 = 0.96. Furthermore, in HAZ simulation fracture initiates earlier and in the zone where HAZ elements were defined, see Figure 9(b). At fracture initiation stress state at HAZ elements was close to plane strain tension, stress triaxiality of ~0.6. Eventually this earlier fracture initiation leads to a torn panel that has larger opening compared with noHAZ design (see Figure 9a).

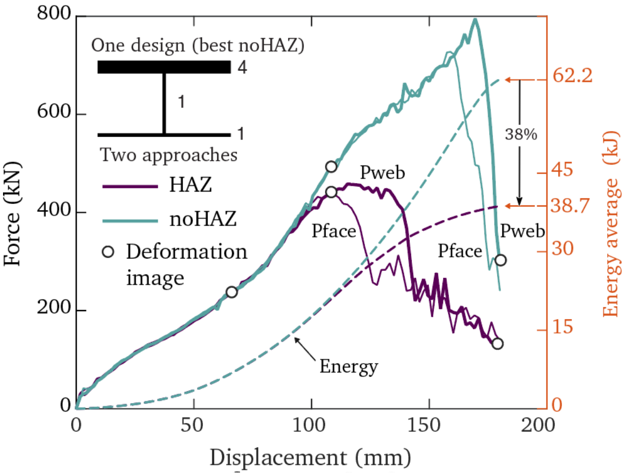

Figure 8. Response of geometrically similar panels modelled using two approaches, with and without HAZ. Circle marker refers to image in Figure 9.

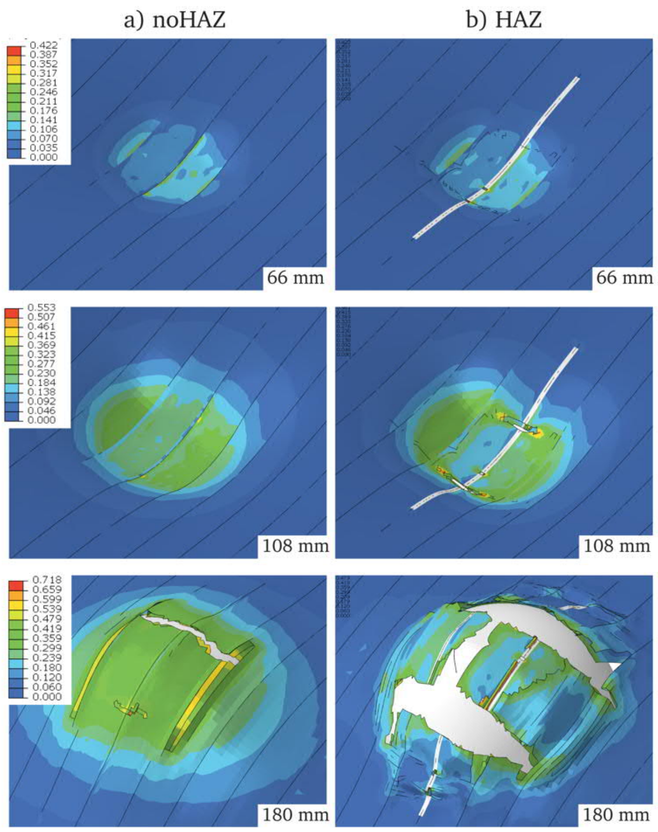

Figure 9. Numerical simulation results with the same geometry (best noHAZ), but different modelling approach. Indenter in position Pweb. a) Welds not modelled (noHAZ approach). b) Welds modelled (HAZ approach). Contours show equivalent plastic strain.

4 CONCLUSION

The objective of the paper was to show the effect of modelling welds when optimizing for crashworthiness. Such optimizations are frequently performed to show the benefits of novel design methods and to ultimately design structures that contribute to safety. Here, steel web core sandwich panel was selected for optimization. Because of the simple geometry the amount of deformation pathways is limited. In spite of this simplicity, optimization results with and without HAZ showed differences that cannot be ignored when optimization for crash is performed. Comparison of two modelling techniques, namely with and without HAZ, showed that objective function in optimization, the U/M ratio, decreased 11% when HAZ was modelled. More striking however, was the difference in geometry of best designs. Design without welds (noHAZ) was lightweight with number of plastic hinges maximized. In contrast, HAZ design had close to maximum weight, with thick top face plate and minimum number of webs.

To further analyse the differences between modelling approaches, we took the optimized noHAZ geometry, but used the HAZ modelling approach. As a result, energy decreased 38%. The U/M ratio was higher for noHAZ approach. This is very concerning considering that noHAZ approach is a conventional way of modelling. This motivates the further investigations in to the effect of welds in complex steel structures subjected to large deformations.

Some important limitations of this study that should be considered in future investigations:

- Heat affected zone was modelled only on one web face interface for simplicity. Modelling in all locations could affect the deformation mechanics when web spacing reduces.
- Fracture in base material was modelled with criterion that depended on length/thickness ratio. In weld elements constant fracture strain was used, although thickness changed. Weld modelling approach should be further validated.
- Stress state effect on failure strain of weld material was not considered. The elements in the heat affected zone experienced plane strain stress triaxiality at the fracture onset.
- Strain rate effect was excluded. This is seen as a reasonable simplification as far as the behaviour under quasi-static loading remains unresolved.

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