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THE EFFECT OF NUMERICAL 2D AND 3D FEM ELEMENT MODELLING ON STRAIN AND STRESS DISTRIBUTIONS AT LASER WELD NOTCHES IN STEEL SANDWICH TYPE PANELS

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ABSTRACT

Like other means of transport, merchant ships face the problem of increasing requirements concerning the environment protection, which, among other issues, implies the reduction of fuel consumption by the ship. Here, the conventional approach which consists in making use of higher strength steels to decrease the mass of the ship hull can be complemented by the use of new steel structures of sandwich panel type. However, the lack of knowledge and experience concerning, among other issues, fatigue strength assessment of thin-walled sandwich structures makes their use limited. Untypical welds imply the need for individual approach to the fatigue analysis. The article presents the effect of numerical FEM modelling with the aid of two-dimensional (2D) and three-dimensional (3D) elements on the results of strain and stress distributions in the areas of toe and root notches of the analysed laser weld. The presented results of computer simulation reveal that modelling of strain and stress states in 2D (instead of full 3D) affects only the results in close vicinity of the notch, and the observed differences rapidly disappear at a distance of 0.05 mm from the bottom of the notch. The obtained results confirm the possibility of use of numerically effective 2D strain and stress state models for analysing the fatigue strength of laser weld according to local approach.

Keywords: ship structure, sandwich, panel, FEM, laser weld, stress, strain, notch, fatigue, lightweight structure, I-core, EEDI

INTRODUCTION

The maritime transport industry plays an important role in the present globalised world. Every day, huge amount of cargo is transported by sea. The total annual volume of the transported cargo is estimated as equal to 53.6 milliard tonnes-sea miles [1]. Despite clear slowdown of the rate of development in recent years, the long-distance maritime transport is irreplaceable, and what is more, is still remains most effective in economic terms. Taking into consideration the emission of greenhouse gases, CO2 in particular, ships are nowadays the most ecological form of transport. Depending on the size, merchant ships emit from 3 to 8 grams of CO_2 per tonne-kilometre of transported cargo [2], while the 18-wheeler based road transport emits about 15 times as much, and the air transport about 80 times as much. In total, the maritime transport emits about 2.5% of all greenhouse gases [3] and still remains the sector which is least burdened with restrictive environment protection regulations. The most significant regulations which aim at reducing the emission of toxic substances (SOx and NOX in particular) during fuel combustion is the MARPOL convention and its Annex VI [4], which introduces limits for permissible emissions of toxic substances during fuel combustion (Tier I, II). Since September 2017, the limit Tier III will apply, which reduces by 70% the permissible emission of toxic substances by ships, compared to Tier II [5]. Although many ship owners make attempts to avoid environment protection related costs, changes in nearest years are inevitable. EU has also introduced regulations for their maritime areas which reduce, since 2020, the content of sulphur in the fuel down to 0.5% [6]. The above regulations mainly refer to the quality of the combusted fuel and obligatory introduction of additional devices to capture toxic substances from the exhaust. Much more interesting changes have been brought by IMO regulations [4], which introduced obligatory requirements concerning ship energy efficiency in order to reduce their negative effect on the environment. A key element here are the Energy Efficiency Design Index (EEDI) [7]–[9] and the Ship Energy Efficiency Management Plan (SEEMP) [10], which entered into force in January 2013 and are obligatory for newly built ships. These regulations impose minimal EEDI values depending on ship's type and size. The planned grow of ship energy efficiency is expected to reach 10%, 20% and 30% until year 2020, 2025 and 2030, respectively. The introduced regulations do not impose the way in which they are to be met, therefore the abovementioned efficiency grow can result either from technological development, or from improvement in the ship maintenance area (better management, for instance).

Accordingly, there is a need for significant grow of economic efficiency of ships. A possible way to reduce fuel consumption and emission of greenhouse gases is decreasing the mass of the ship hull. For medium-size or small ships, there is economically justified possibility of use of aluminium alloys in the superstructure or entire structure of the ship hull. In the case of large merchant ships, so far, the most effective method to decrease the ship hull mass consists in the use of higher strength steels and decreasing the thickness of structural elements. The estimated reduction of ship hull mass resulting from the use of high tensile strength (HTS) steels is shown in Fig. 1. The yield point of HTS steels is 2–3 times as high as that of ordinary strength structural steel (235 MPa). At present, the contribution of higher strength steels in many newly built ships amounts to 80% of ship hull mass.

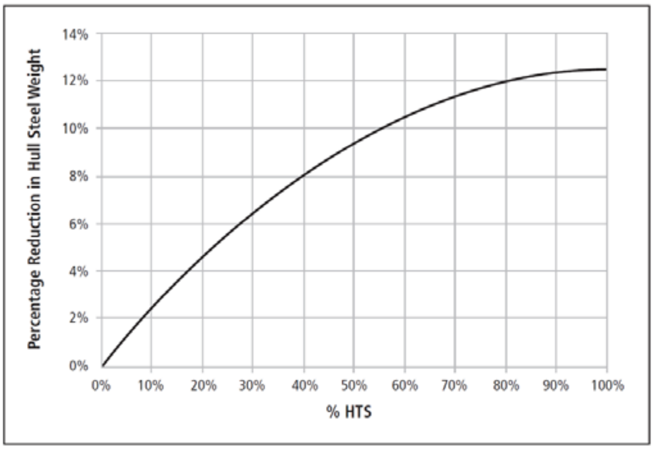

Fig. 1. The effect of HTS steel contribution on ship hull mass reduction [11]

Another way to reduce the ship hull mass is the use of new structural forms, so-called sandwich panel structures. These are multilayer panels made of higher strength steel, but consisting of extremely thin sheets, of t=1.5-5.0 mm in thickness. The panel structure is designed taking into account its specific use and attributing it with the required mechanical and functional properties. The use of different cross-section shapes of internal stiffeners is possible, including I, Y, V, X, or O shapes. For instance, panels with X and Y type stiffeners (optionally with inner core) reveal higher ability to absorb energy during collision [12], [13], [14], [15], [16], [17]. Other variants of multilayer structures with advanced mechanical properties resulting from the use of light concrete as filling material can be found in [18], [19], [20]. Thus, depending on the planned application, sandwich structures can have different types of stiffeners, different dimensions of individual structural components, and additional inner space filling. What is of high importance here is the possibility to optimize the structure for selected design assumptions [21], [22], [23]. Within a huge variety of possible solutions, the most frequently used steel sandwich panel form is the I-core panel which consists of two layers of plating separated by internal flat-bar stiffeners. A sample I-core panel with plating thickness of t=2.5mm, FB40x3 stiffeners, and the distance between stiffeners equal to s=120 mm, is shown in Fig. 2.

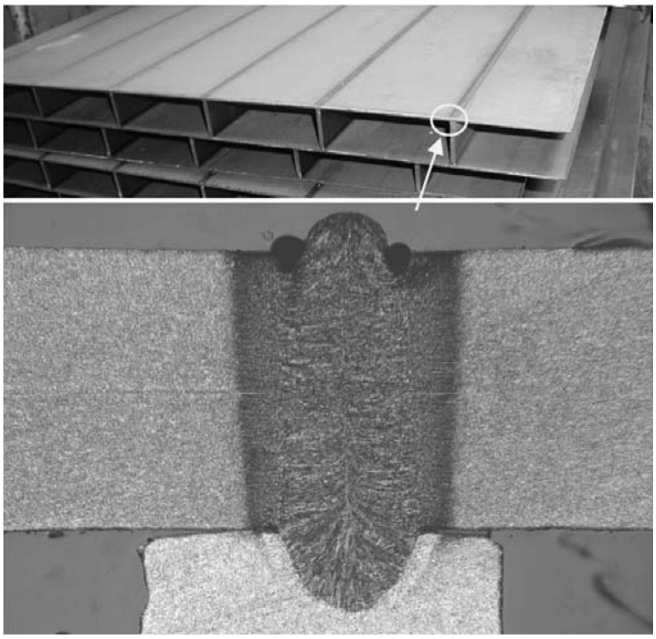

Fig. 2. Steel I-core panel and magnified image of the laser weld connecting the plating with the stiffener.

Despite very favourable mechanical properties and relatively low mass, the use of steel sandwich panels is rather limited now. Among other reasons, this results from the lack of knowledge and experience concerning the safety of use of this new structural solution. A key problem here is assessing the fatigue strength of untypical laser welds connecting the plating with the stiffeners – see Fig. 1. These welds are made using laser welding technology, or its hybrid version also making use of laser. The resultant welded joint has the geometry and material properties which differ much from conventional welds [24], [25], [26], [27]. This significantly affects fatigue characteristics of the thin-walled sandwich structures. Theoretical and experimental research activities are in progress now which focus on assessing the fatigue life of laser welded sandwich structures [28], [29], [30], [31], [25], [32], [32], [32], [33], [34], [35]. The present state of the art in this area has not permitted development of a comprehensive calculation method for structures of this type. The calculated fatigue life of the analysed structures heavily depends on the assumed loading condition [30], [36], [37]. From among numerous possible methods to assess the fatigue life, the most frequent approach bases on local strains, or local stresses [38], [39], [40], [41], [42]. A crucial function in this method is played by stress and strain distributions in the geometric weld notch areas. The most effective way to determine the maximal stress and strain values is computer simulation making use of the Finite Element Method. Simultaneously, the use of the local stress based method requires an individual approach focused on analysing the effect of numerical modelling on the results. An interesting issue in this context is the effect of the computational grid in the notch area observed in analyses of geometric notches, [43] for instance. The dissimilarity of the analysed lased weld results from the use of untypical laser welding technology which consists in one-sided introduction of laser beam from the outer side of the plating and melting it together with the stiffener situated inside it. As a result, a welded joint with untypical geometry and material properties is formed. The effect of the material model on strain and stress distributions will be discussed in a separate paper, while the effect of the rounding radius of the notch on the geometric stress concentration factor was analysed in [44]. For a selected weld variant, the numerically simulated strain field in the notch area was compared with that recorded in the real-scale experiment [45]. As a continuation of earlier research activities in this field, the present article analyses the effect of numerical FEM modelling with the aid of 2D and 3D elements on stress and strain distributions in the notch areas of the analysed laser weld. The analysis is performed from the perspective of use of the determined strain and stress distributions for assessing the fatigue life in so-called local stress/strain approach.

THE EFFECT OF NUMERICAL FEM MODELLING MAKING USE OF 2D AND 3D ELEMENTS

Below described is the numerical model of laser weld in I-core panel. The performed analysis aimed at assessing the effect of the selected way of modelling (2D or 3D) on strain and stress results in the area of geometric toe and root notches of the laser weld. The use of 2D elements assumes the plain strain or stress state, while the use of 3D elements takes in to account the three-axial state of strain and stress.

NUMERICAL MODEL OF LASER WELD

The analysed laser weld was modelled using the FEM method in the computer programme ANSYS. The geometry of the modelled weld was assumed based on the measurements done on samples taken from real panels. The measurements made use of a computer programme and the 25 times magnified photo of the weld. When modelling, the symmetry of the weld geometry with respect to its axis was assumed. The computations were performed for nominal load σ_x = 168 MPa, introduced at the plating sheet edge at a distance from the analysed weld. A linear material model was used which corresponded to steel with Young's modulus E=2.05e5 MPa and Poisson's ratio equal to 0.3. The numerical model with the assumed load and boundary conditions is shown in Fig. 3. The model nodes situated along the weld axis were deprived of the degree of freedom in the x-axis direction, while those situated on the lower edge of the stiffener – in the y-axis direction. The coordinate system shown in the figure is coherent with that used during the presentation of results.

Three variants of numerical models were considered. The first model was created using 3D elements of SOLID186 type which take into account the three-axial strain and stress state. The element SOLID186 has 20 nodes, with three degrees of freedom at each node: in the x-, y-, and z-axis directions. This model was referred to as "solid". The second model, referred to as "pstress", was created using 2D elements of PLANE183 type, in the plain stress state on the xy-plane. The element PLANE183 has 8 nodes, with two degrees of freedom at each node: in the x- and y-axis directions. The last model was also created using the elements PLANE183. It assumed the plain strain state in the xy-plane and therefore was referred to as "pstrain". For all models, the calculations were performed for the same loads, boundary conditions, and discretisation. Below described is the effect of the model version on local strain and stress results in direct vicinities of geometric toe and root notches of the analysed weld.

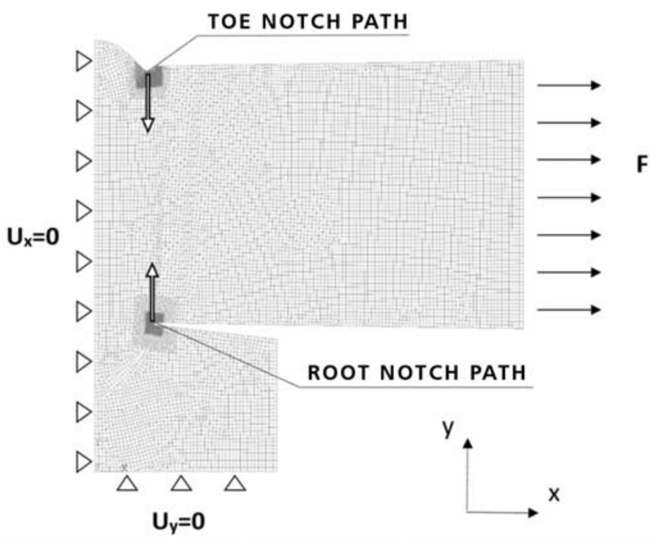

Fig. 3. Numerical FEM model with load and boundary conditions.

RESULTS AND DISCUSSION

The results are analysed along two paths. The first path begins at the weld toe notch and goes down vertically inside the material, while the second path begins at the bottom of the weld root notch and goes up vertically, in the material thickness direction. These two paths are shown in Fig. 3. The results are presented in the form of strain and stress diagrams: in Fig. 4 and Fig. 5 for the toe notch, and in Fig. 6 and Fig. 7 for the root notch. When analysing the results shown in the diagrams we can observe that:

a) The maximal absolute strain and stress values for toe notches are larger than those for root notches. For the toe notch and three-axial strain and stress state modelling:
   – the maximal total strain in the x-axis direction is 0.004186 [-],
   – the maximal total strain in the y-axis direction is 0.002403 [-],
   – the maximal stress Sx in the x-axis direction is 533 MPa,
   – the maximal stress Sy in the y-axis direction is 38 MPa,

   Relative differences of maximal strain values in the x- and y-axis directions in the root notch area are equal to -24.6% and -41.6%, respectively, while for the stresses Sx and Sy they are equal to -7.8% and 109.9%, respectively. The stress values in the x-axis direction are 14 times as large for the toe notch and 6 times as large for the root notch as those in the y-axis direction. Based solely on the results of the numerical FEM analysis, the maximal strain and stress values are observed in the toe notch, and this notch can be indicated as the possible place of fatigue crack concentration. However, the experimental weld fatigue research shows that in practice, fatigue cracks are observed in both toe and root notches. There is no sufficient experimental evidence to indicate univocally the place in which the fatigue cracks occur much more frequently. This issue needs more experimental research.

b) For both the toe and root notches, greater strain and stress values are observed in the x-axis direction. In three-axial strain and stress state modelling, the maximal toe notch strain value in the y-axis direction is equal to 57.4% of that in the x-axis direction. For the root notch this value is 44.5%. The maximal toe notch stress value in the y-axis direction is equal to 7.1% of that in the x-axis direction, while for the root notch this value is 16.2%. This results directly from the load direction assumed in the calculations, which was the x-axis direction. What is also noteworthy is large strain and stress values in the y-axis direction (perpendicular to the direction of load action).

c) The results for the plain stress state at the notch bottom differ from the remaining values, but at the distance of 0.05 mm from the notch bottom this difference disappears. For instance, the relative difference of normal toe notch stress Sx between the plain stress state model and the thee-axial stress state model is equal to 34.9%, while at the distance of 0.05 mm this difference drops down to as little as 8.3%.

d) The plain strain state calculation variant gives the strain results close to those obtained in the three-axial strain and stress state modelling. This is because of the assumed zero stress value in the direction normal to the finite element plane. Likewise, the plain stress state variant gives the stress results close to those obtained in the three-axial strain and stress state variant, due to the assumed zero strain value in the direction normal to the finite element plane.

e) For all analysed variants, the compliance of strain and stress results is much better in the y-axis direction than that in the x-axis direction, which is related with the direction of load action. The effect of the assumed zero strain and stress values in the plain stress and strain variants, respectively, is less noticeable in the less heavily loaded direction.

The above results reveal that plain strain state modelling makes it possible to obtain local strain and stress results similar to those obtained in the three-dimensional model. In the fatigue analysis according to local approach, the effective notch stress is determined in accordance with the hypothesis of stress averaging at a virtual distance of microstructural support, or at a distance of fictional notch rounding radius [38]. In both cases the distance at which the results are averaged is greater than the distance from the notch bottom at which the effect of modelling on the results can be observed. Thus, from the practical point of view, the results of geometric stress concentration coefficients will be identical for all here analysed methods of modelling.

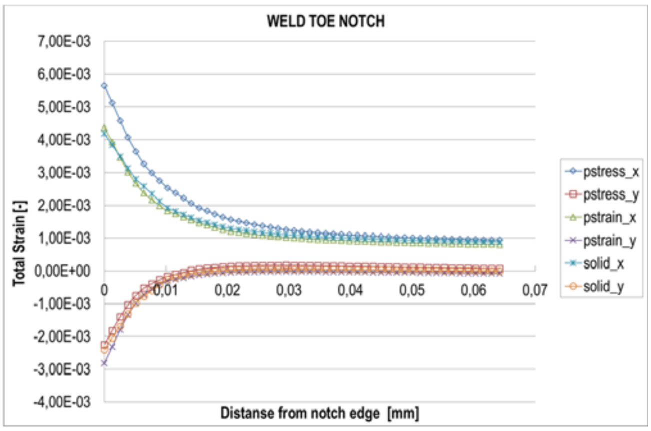

Fig. 4. Total strain in x- and y-axis directions for laser weld toe notch path

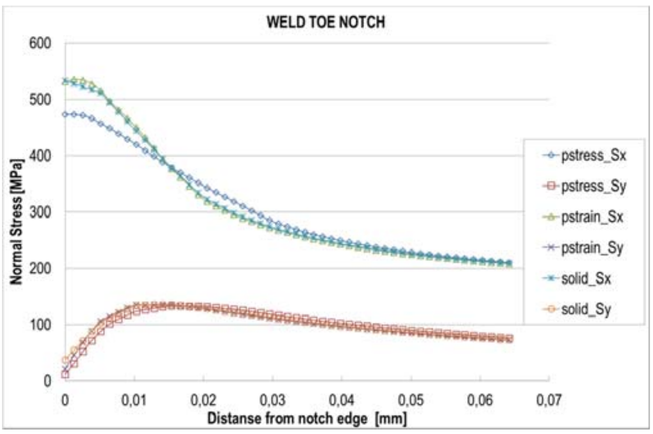

Fig. 5. Normal stress in x- and y-axis directions for laser weld toe notch path

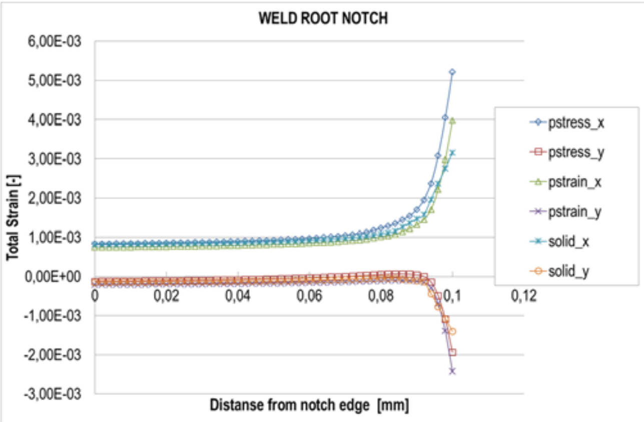

Fig. 6. Total strain in x- and y-axis directions for laser weld root notch path.

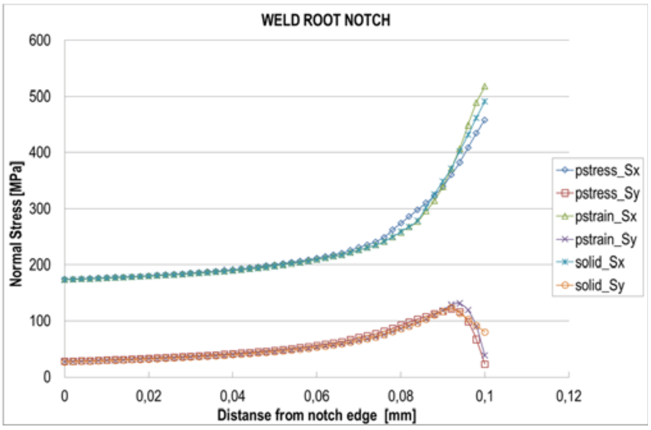

Fig. 7. Normal stress in x- and y-axis directions for laser weld root notch path.

SUMMARY AND CONCLUSIONS

The need to fulfil new requirements concerning ship energy efficiency improvement implies technological progress aiming at the reduction of fuel consumption and emission of greenhouse gases. Taking into account economic and ecological aspects, of high importance here is the reduction of ship hull mass. A commonly used approach to reach this goal is the use of higher strength steels. In many cases the contribution of HTS steels in the hull structure can reach as much as 60-80%. Cases have been reported when the ships were entirely (100%) built of higher strength steel. We can say that this method of ship hull mass reduction has been exploited. New opportunities are opened by the use of new structures, so-called sandwich panels. They are also made of higher strength steels, but the sandwich type structure makes it possible to reach much more favourable relation of strength properties (stiffness in particular) to mass. Research activities are in progress now which focus on determining a series of properties of sandwich structures in order to ensure safety of their use. An important aspect which needs a detailed analysis is the fatigue life of welds connecting structural elements of panels. Compared to typical joints, these welds have considerably different geometry and material properties, which implies the need to examine the effect of these differences on the fatigue life of welds. The analysis can be performed using the local stress or local strain approach, whereas the strain or stress distributions at the notch are usually determined based on computer simulations performed with the aid of the Finite Element Method or the Boundary Element Method. The fatigue life calculation methodology is known for welds connecting structural elements of more than 5 mm in thickness. The application of this methodology for thinner elements, such as steel sandwich panels, implies the need for verifying the effect of particular aspects of numerical modelling on the obtained results. This article analysed the effect of 2D and 3D modelling on the strain and stress distributions at geometric nodes of the laser weld made in the steel I-core panel. The calculations were performed using the Finite Element Method in three variants characterised by: plain stress state, plain strain state, and three-axial strain and stress state. The obtained results have revealed that the effect of modelling method on the results at the bottom of the weld toe and root notch is small. The strain and stress results in the toe and root notch areas obtained using the plain strain and plain stress models are very close to those obtained using the three-axial strain and stress model. Differences in local strain or stress values disappear at such a small distance as about 0.05 mm from the notch bottom. When performing the fatigue analysis in accordance with the local approach (local strain or local stress), the effective stress values are determined at a virtual distance of microstructural notch support, or at a distance of fictional notch rounding radius. It is noteworthy that regardless of the stress averaging method, the distance at which it is done is greater than the distance from the notch bottom at which the effect of the modelling method on the values of the analysed strain or stress is noticeable. Therefore, the important practical conclusion is that the geometric stress concentration coefficient values calculated using 2D plain strain modelling, 2D plain stress modelling, and 3D three-axial strain and stress modelling will be very close to each other, and the possible effect of modelling method can be neglected. This justifies the use of much more effective 2D models for analysing strain and stress concentrations in laser weld toe and root notches.

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BIBLIOGRAPHY

1. UNCTAD, “Review of Maritime Transport 2016,” 2016.
2. P. R. Cabezas and G. Kasoulides, “International Maritime Organization,” Int. J. Mar. Coast. Law, vol. 3, no. 3, pp. 235–245, 2004.
3. T. W. P. Smith et al., “Third IMO Greenhouse Gas Study 2014,” 2014.
4. IMO, “MARPOL Annex VI, Chapter 4,” 2011.
5. IMO, “MEPC 69/21. Report of the Marine Environment Protection Committee on its sixty-ninth session,” 2016.
6. European Parliament and Council of the European Union, “Directive 2012/33/EU of the European Parliament and of the Council,” 2012.
7. IMO, “MEPC.215(93) – Guidelines for calculation of reference lines for use with the Energy Efficiency Design Index (EEDI),” 2012.
8. IMO, “MEPC.214(93) – 2012 Guidelines on survey and certification of the Energy Efficiency Design Index (EEDI),” 2012.
9. IMO, “MEPC.212(93) – 2012 Guidelines on the method of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships,” 2012.
10. IMO, “MEPC.213(93) – 2012 Guidelines for the development of a Ship Energy Efficiency Management Plan (SEEMP),” 2012.
11. American Bureau of Shipping, “Ship Energy Efficiency Measures - Status and Guidance,” 2013.
12. H. Naar, P. Kujala, B. C. Simonsen, and H. Ludolphy, “Comparison of the crashworthiness of various bottom and side structures,” Mar. Struct., vol. 15, no. 4–5, pp. 443–460, 2002.
13. A. Klanac, S. Ehlers, and J. Jelovica, “Optimization of crashworthy marine structures,” Mar. Struct., vol. 22, no. 4, pp. 670–690, 2009.
14. P. Hogstrom and J. W. Ringsberg, “Assessment of the crashworthiness of a selection of innovative ship structures,” Ocean Eng., vol. 59, pp. 58–72, 2013.
15. V. Rubino, V. S. Deshpande, and N. A. Fleck, “The collapse response of sandwich beams with a Y-frame core subjected to distributed and local loading,” Int. J. Mech. Sci., vol. 50, no. 2, pp. 233–246, 2008.
16. L. St-Pierre, V. S. Deshpande, and N. A. Fleck, “The low velocity impact response of sandwich beams with a corrugated core or a Y-frame core,” Int. J. Mech. Sci., vol. 91, pp. 71–80, 2015.
17. S. Hou, S. Zhao, L. Ren, X. Han, and Q. Li, “Crashworthiness optimization of corrugated sandwich panels,” Mater. Des., vol. 51, pp. 1071–1084, 2013.
18. A. Christian and G. O. K. Chye, “Performance of fiber reinforced high-strength concrete with steel sandwich composite system as blast mitigation panel,” in Procedia Engineering, 2014, vol. 95, pp. 150–157.
19. E. A. Flores-Johnson and Q. M. Li, “Structural behaviour of composite sandwich panels with plain and fibre-reinforced foamed concrete cores and corrugated steel faces,” Compos. Struct., vol. 94, no. 5, pp. 1555–1563, 2012.
20. T. J. Grafton and J. R. Weitzenböck, “Steel-concrete-steel sandwich structures in ship and offshore engineering,” Adv. Mar. Struct. - Proc. 3rd Int. Conf. Mar. Struct. MARSTRUCT 2011, pp. 549–558, 2011.
21. J. Romanoff and P. Kujala, “OPTIMUM DESIGN FOR STEEL SANDWICH PANELS FILLED WITH POLYMERIC FOAM,” in FAST 2001 The 6th International Conference on Fast Sea Transportation, 2001, no. September.
22. J. D. Poirier, S. S. Vel, and V. Caccese, “Multi-objective optimization of laser-welded steel sandwich panels for static loads using a genetic algorithm,” Eng. Struct., vol. 49, pp. 508–524, 2013.
23. J. Romanoff, “Optimization of web-core steel sandwich decks at concept design stage using envelope surface for stress assessment,” Eng. Struct., vol. 66, pp. 1–9, 2014.
24. D. Boroński, “Cyclic material properties distribution in laser-welded joints,” Int. J. Fatigue, vol. 28, no. 4, pp. 346–354, 2006.
25. J. Kozak, “Selected problems on application of steel sandwich panels to marine structures,” Polish Marit. Res., vol. 16, no. 4, pp. 9–15, 2010.
26. H. Remes and P. Varsta, “Statistics of Weld Geometry for Laser-Hybrid Welded Joints and its Application within Notch Stress Approach,” Weld. World, vol. 54, no. 7, pp. R189–R207, 2010.
27. R. Soltysiak and D. Boronski, “Strain analysis at notch root in laser welded samples using material properties of individual weld zones,” Int. J. Fatigue, vol. 74, pp. 71–80, 2015.

28. N. A. McPherson, N. Suarez-Fernandez, D. W. Moon, C. P. H. Tan, C. K. Lee, and T. N. Baker, “Laser and laser assisted arc welding processes for DH 36 microalloyed steel ship plate,” Sci. Technol. Weld. Join., vol. 10, no. 4, pp. 460–467, 2005.

29. V. Caccese, P. A. Blomquist, K. A. Berube, S. R. Webber, and N. J. Orozco, “Effect of weld geometric profile on fatigue life of cruciform welds made by laser/GMAW processes,” Mar. Struct., vol. 19, no. 1, pp. 1–22, 2006.

30. C. M. Sonsino, M. Kueppers, M. Eibl, and G. Zhang, “Fatigue strength of laser beam welded thin steel structures under multiaxial loading,” Int. J. Fatigue, vol. 28, no. 5–6, pp. 657–662, 2006.

31. K. Salonitis, P. Stavropoulos, A. Fysikopoulos, and G. Chryssolouris, “CO2 laser butt-welding of steel sandwich sheet composites,” Int. J. Adv. Manuf. Technol., vol. 69, no. 1–4, pp. 245–256, 2013.

32. D. Frank, J. Romanoff, and H. Remes, “Fatigue strength assessment of laser stake-welded web-core steel sandwich panels,” Fatigue Fract. Eng. Mater. Struct., vol. 36, no. 8, pp. 724–737, 2013.

33. D. Frank, J. Romanoff, and H. Remes, “Fatigue life improvement of laser-welded web-core steel sandwich panels using filling materials,” in Analysis and Design of Marine Structures - Proceedings of the 5th International Conference on Marine Structures, MARSTRUCT 2015, 2015.

34. A. T. Karttunen et al., “Fatigue strength of laser-welded foam-filled steel sandwich beams,” Mater. Des., vol. 115, pp. 64–72, 2017.

35. J. W. Sowards et al., “Low-cycle fatigue behavior of fiber-laser welded, corrosion-resistant, high-strength low alloy sheet steel,” Mater. Des., vol. 121, pp. 393–405, 2017.

36. W. Fricke, C. Robert, R. Peters, and A. Sumpf, “Fatigue strength of laser-stake welded T-joints subjected to combined axial and shear loads,” Weld. World, vol. 60, no. 3, pp. 593–604, 2016.

37. D. Frank, P. Dissel, H. Remes, J. Romanoff, and O. Klostermann, “Fatigue strength assessment of laser stake-welded T-joints subjected to reversed bending,” Fatigue Fract. Eng. Mater. Struct., vol. 39, no. 10, pp. 1272–1280, 2016.

38. D. Radaj, C. M. Sonsino, and W. Fricke, Fatigue assessment of welded joints by local approaches. 2006.

39. D. Radaj, C. M. Sonsino, and W. Fricke, “Recent developments in local concepts of fatigue assessment of welded joints,” Int. J. Fatigue, vol. 31, no. 1, pp. 2–11, 2009.

40. C. M. Sonsino, W. Fricke, F. De Bruyne, A. Hoppe, A. Ahmadi, and G. Zhang, “Notch stress concepts for the fatigue assessment of welded joints - Background and applications,” Int. J. Fatigue, vol. 34, no. 1, pp. 2–16, 2012.

41. D. Frank, “Fatigue strength assessment of laser stake-welded T-joints using local approaches,” Int. J. Fatigue, vol. 73, pp. 77–87, 2015.

42. K. Niklas, “Calculations of notch stress factor of a thin-walled spreader bracket fillet weld with the use of a local stress approach,” Eng. Fail. Anal., vol. 45, 2014.

43. A. Cichanski, “The influence of mesh morphology on the SCF in 2D FEM analysis of flat bars with opposite V-notch under tension,” in 22nd International Conference on Engineering Mechanics, 2016, pp. 110–113.

44. K. Niklas and J. Kozak, Influence of the notch rounding radius on estimating the elastic notch stress concentration factor in a laser welded tee joint, vol. 726. 2012.

45. Niklas K.; Kozak J., “Comparison of strain results at a laser weld notch obtained by numerical calculations and experimental measurements,” AIP Conf. Proc. 1780, Am. Inst. Phys., 2016.

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