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Influence of weld-induced distortions on the stress magnification factor of a thin Laser-hybrid welded Ship deck panel

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ABSTRACT: The limited knowledge about fatigue behavior and lack of analytical solutions for distorted thin plates are predominantly limiting their application today. This paper focuses on finding the most influential distortion parameter that dictates the fatigue strength at the butt weld of a laser-hybrid welded 4 mm thin ship deck panel. A FEA based sensitivity analysis method is employed to identify the influence of the distortion parameters. The results from the experimental validation showed that the distortions of the distorted deck plate on either side of the butt weld could be simplified with 4-point and 3-point splines on longitudinal and transversal direction, respectively. The most important distortion parameters are local angular misalignment, the distortion magnitude and location of local maximum distortion close to the butt weld. The distortion parameters further away from the weld has a minor influence on the structural stress at the butt weld. Furthermore, the results showed that the local angular misalignment can independently provide a better estimate of stress magnification factor k_m compared to any other distortion parameters.

1 INTRODUCTION

Advanced steel materials combined with modern manufacturing technologies make it possible to design and manufacture thinner and lighter components leading, for example, to a lightweight design of ship. Reduced weight due to lighter structures would offer a significant increase in payload, higher fuel efficiency, as well as more freedom in the design of exotic vessels while reducing the carbon footprint. The implementation requires, however, a deep understanding of the loads and responses during the intended application of the thinner plates (t = 4 mm). This paper intends to highlight the limitations of the current rules and recommendations for fatigue estimation in distorted thin welded plates and suggest improvements to better estimate the fatigue life of such components.

Welded panels have local and global distortions formed during its production, for instance, during manufacturing of the plates, transportation, storing, and most significantly during welding. Thinner plates have lower bending stiffness than thicker ones, resulting in a higher susceptibility to weld–induced distortions and misalignments during the welding operation (Lillemäe et al 2012, Eggert et al 2012). Laser-hybrid welding has a lower heat input compared to the commonly used shielded metal arc welding (Fricke et al 2015, Gupta 2017), which leads to smaller welding-induced distortions, better weld quality and consequently longer fatigue life (Remes et al 2017). Still, with the thinner plates, welding induced distortions possess a significant impact on the fatigue life of deck panels as observed in previous research (Lillemäe et al 2017, 2012, Remes & Fricke 2014, Lillemäe-Avi et al 2017, Remes et al 2017).

Several studies have been performed to analyze and quantify the effect of geometrical imperfections on welded structures in thin plates (Fricke et al 2015, Fricke & Feltz 2013, Lillemäe et al 2016, 2017, Liinalampi et al 2016, Remes & Fricke 2014, Eggert et al 2012, Lillemäe-Avi et al 2017, Remes et al 2017). The full-scale fatigue test by Lillemäe et al (2017) showed a strong influence of shape and geometrical nonlinearity due to distortions on the structural stress of the deck panels. The distortions cause redistribution of the membrane stresses, increasing the stresses near the boundaries (Fricke & Feltz 2013). These stresses are higher compared to the total stresses consisting of membrane and bending stresses within the plate field (Fricke & Feltz 2013). Along with that, the straightening effect due to the application of tensile load also interferes with the fatigue behavior of the structure (Lillemäe et al 2016, Kuriyama et al 1971). For thin plated deck panels, it was discovered that the angular misalignment is more critical when it forms a roof like appearance in the butt-welded panels (Eggert et al 2012). Furthermore, the distortion shape is different for thin welded plates from that of thick plates as shown in Figure 1. For, thin-welded panels (see Fig. 2), the experiments showed a half sine-wave-like shape in the transverse direction and several half sine waves in the longitudinal direction as shown in Figure 3 and Figure 4 above (Lillemäe-Avi et al 2017, Eggert et al 2012).

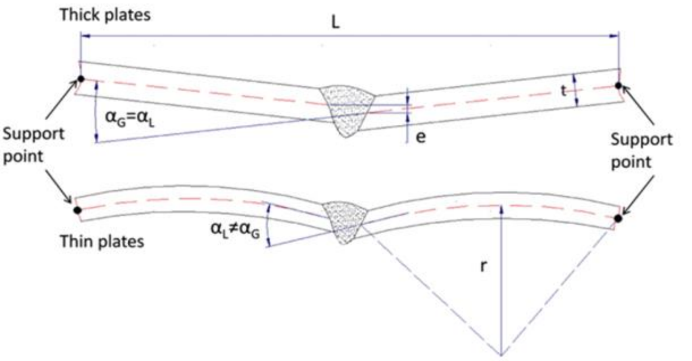


Figure 1. Angular misalignment (α) and axial misalignment (e) as well as simplified plate distortion due to welding (Lillemäe et al. 2012)

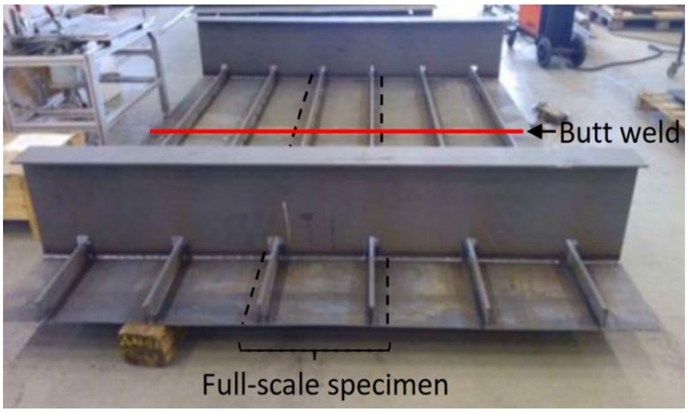


Figure 2. Experimental specimen for fatigue tests from a 4 mm thick cruise ship deck panel (Lillemäe-Avi et al. 2017)

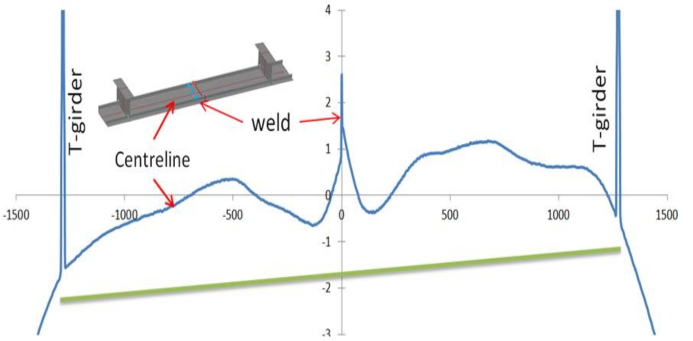


Figure 3. Deformation after welding on the longitudinal direction of deck panel at its centerline, green bar shows an ideal straight panel.

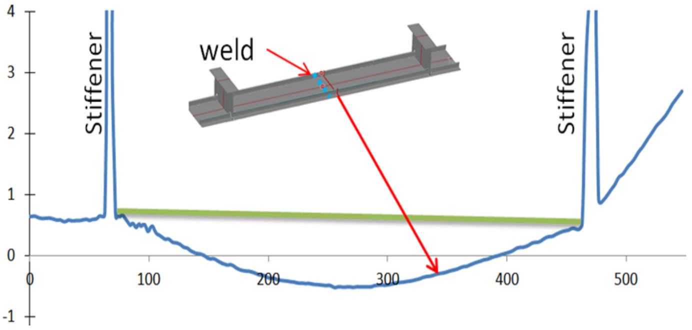


Figure 4. Deformation after welding on the transversal direction at 100 mm from weld seam, green bar shows an ideal straight panel.

The existing structural hot-spot extrapolation methods were successfully utilized in FEA for thin welded panels with complex distortion shapes and geometrical non-linearity (Fricke & Feltz 2013, Liinalampi et al 2016, Eggert et al 2012, Lillemäe et al 2017, Lillemäe-Avi et al 2017). When an initially distorted panel is loaded, local secondary bending effect in the panel causes geometrically non-linear behavior; such response is considered in non-linear FEA. Thus, the stress magnification factor $k_{m,FEA}$ due to misalignments and distortions is evaluated from non-linear FEA as shown in Equation 1.

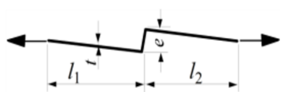
$$k_{m,FEA} = \frac{\sigma_{hs}}{\sigma_{nom}} \qquad (1)$$

where σ_{hs} is structural stress and σ_{nom} is nominal stress on the panel e.g. ship deck structure. However, this approach differ from the current classification guidelines or design recommendation, which utilizes the analytical k_m equations to consider secondary bending stress due to distortion and misalignments.

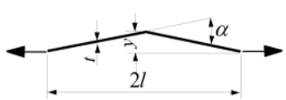
The analytical equations of IIW recommendation for structural stress mentions the method to consider misalignments under axial loading as well as the straightening effect. The straightening effect in the plate has been included with a tanh correction factor as shown in Equation 3 (Hobbacher 2009). However, the tanh correction factor assumes that the initial distortions are in a straight line, which is not the case in the distorted panels. Similarly, BV (Bureau Veritas 2016) and DNV (DNV GL 2015) standards have recommendations for stress magnification factors in cases of axial and angular misalignments. However, neither of these recommendations have taken the effect of curvature due to welding induced distortions in flat plates into account. There are no rules devised to describe the methods of estimating such distortions and evaluate the impact of each distortion parameter on the structural behavior of a distorted plate. The class rules have not even taken straightening effect of angular misalignment into account.

The IIW recommendation provides analytical formulae for stress magnification factor with angular and axial misalignments under axial loading for flat plates with equal thickness as shown in Equation 2,3 and 4 (Hobbacher 2009). They are combined to give the stress magnification factor (k_m) by Equation 5.

$$k_{m,axial} = 1 + \lambda \frac{e \cdot l_1}{t(l_1 + l_2)} \qquad (2)$$



$$k_{m,angular} = 1 + \frac{3y}{t} \cdot \frac{\tanh(\beta/2)}{\beta/2} \qquad (3)$$



$$k_{m,angular} = 1 + \frac{3\alpha l}{2t} \cdot \frac{\tanh(\beta/2)}{\beta/2} \qquad (4)$$

$$k_m = 1 + (k_{m,axial} - 1) + (k_{m,angular} - 1) \qquad (5)$$

where e is the axial misalignment, t is the plate thickness, α is the angular misalignment in radians, l is the support length, y is the lateral distortion and β is evaluated as:

$$\beta = 1 + \frac{2l}{t} \cdot \sqrt{\frac{3\,\sigma_m}{E}} \qquad (6)$$

where, σ_m is the membrane stress.

The equations for k_m have λ and β parameters that depend on the boundary conditions. The value of λ is 6 for unrestrained joints, and in remotely loaded panels, $l_1 = l_2$ is assumed (Hobbacher 2009).

A clear definition of angular misalignment and analytical k_m equations for distorted thin panels are not established yet, which is limiting the application of thin plates into practice. Therefore, this paper focuses on finding the most influential distortion parameter that dictates the fatigue strength of 4 mm thin ship deck panel. Multiple series of sensitivity analyses were performed on 3D models of the distorted deck panels in order to understand the influence of distortion on their fatigue behavior. The effects of local angular misalignment and the effect of overall plate distortion on the stress magnification factor at root of butt weld of the deck panel are studied. The effect of axial misalignment is excluded from the this study as the acceptable limits for manufacturing are available (Germanischer Lloyd 1996, Nihon-Zōsen-Gakkai and Research Committee on Steel Shipbuilding 1985, ISO 5817:2014 2014).

2 METHOD

The distorted geometries for the fatigue sensitivity analysis were prepared based on fthe distortion behavior of the scanned panels from previous research (Lillemäe et al 2017, Lillemäe-Avi et al 2017) as shown in Figure 5.

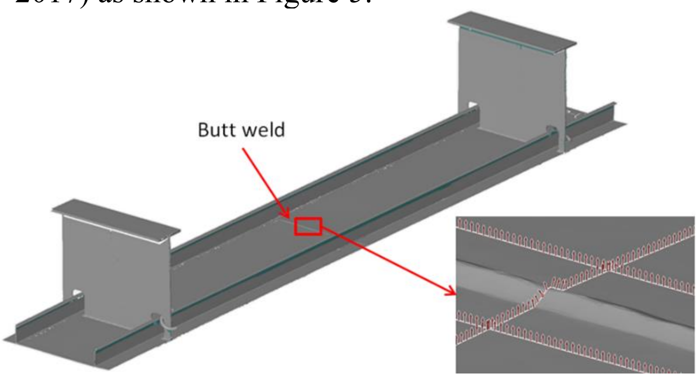


Figure 5. Scanned geometry of the panel shown in Figure 2 with GOM software, and measured points on the selected cross-section near the weld.

The distorted shapes of the panels were simplified in the longitudinal as well as transverse directions. Control curves to make parametric model of distorted panels were designed by manually fitting curves over actual distortion profiles as shown in Figure 6. Due to the large variation in the distortion pattern, several simplified contours were created to control the deformed shape at various locations of the distorted model. The distortion seems to follow either a half-wave like profile from the weld seam to the support or a multiple of such half waves. Few panels from Lillemäe et al (2017) had small wavy distortions with up to 5 half–waves on either side of the weld seam, however, they were all following similar global distortion pattern with one full–wave on either side of the weld seam. Based on these observations, two control curves were idealized to make parametric model of ship deck panel with distorted geometry as shown in Figure 7. After the distortion parameters were established, a library of distorted models was systematically created. The structural hot-spot stress data was extracted from non-linear FEA of each model and results were compared.

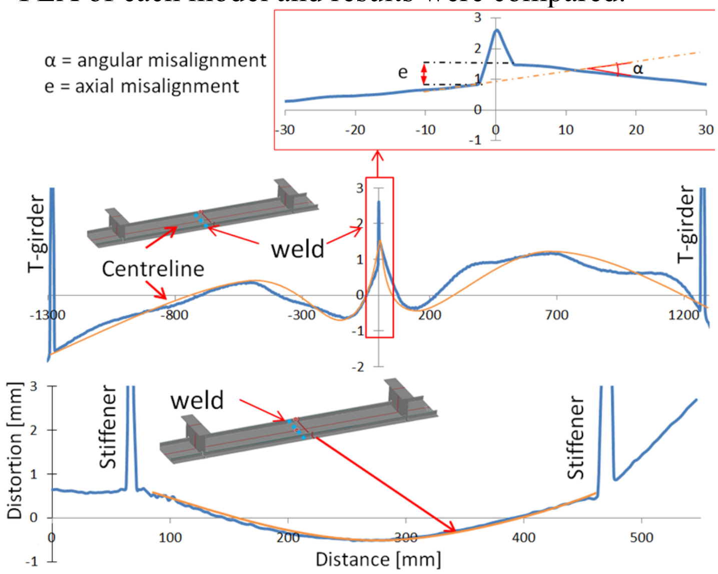


Figure 6. Simplification of the distortion shapes, longitudinal direction on top, and transverse direction on the bottom. Blue line represents the distortion profile and orange line is the simplified control curve for modelled panel.

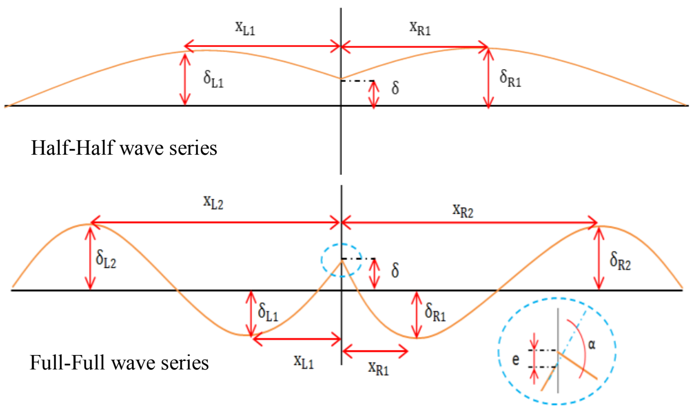


Figure 7. Idealized deformation shapes along the longitudinal direction of the deformed geometry with variable parameters for sensitivity analysis.

The distortion parameters along the transverse direction (parallel to butt weld) of the panel were coupled with that of the longitudinal direction (normal to the butt weld). The change in the distortion parameters along longitudinal direction included the changes in transverse direction, therefore only the variables along longitudinal direction as shown in Table 1 were studied.

Table 1. The list of distortion parameters along longitudinal direction.

Variable parameters	Description
δ	Lateral distortion of the weld seam
$x_{L1}, x_{R1}, x_{L2}, x_{R2}$	Location of maximum distortions
$\delta_{L1}, \delta_{R1}, \delta_{L2}, \delta_{R2}$	Maximum distortions
α*	Local angular misalignment
e**	Axial misalignment

* It is a dependent variable; therefore, it is measured from the distorted models; it is not applied as a controlling parameter.
** Axial misalignment is excluded from this research, as there are existing limits for manufacturing.

The subscript L and R denote 'to the left' and 'to the right' of weld seam respectively. The subscripts 1 and 2 after the letter L or R represents the number of half-waves from the butt weld seam where 1 represents the first half-wave and 2 represents the second half-wave.

Two families of distorted models were created: half-half wave series with one half-wave like distortion on either side of weld seam, and full-full wave series with one full-wave like distortion on either side of the weld seam. The models in each series of the families were created with varying magnitude of one or two distortion parameters while keeping the other parameters constant. The parameters varied and the range of magnitude for such variation are presented in sub-sections 2.1 and 2.2 below.

2.1 *Half-half wave family*

The distorted models of half-half wave family were further divided into five series, each representing one or combination of two distortion parameters being studied as listed in Table 2 below.

Table 2. Half-half wave family series.

half-half wave series	Description
101_δ	Lateral distortion (δ) varied
101_δL1	Maximum distortion of the first half wave on left side of weld seam varied
101_δL1δR1	Maximum distortion of the first half wave on left and right side of weld seam varied
101_xL1	Location of maximum distortion of the first half wave on left side of weld seam varied
101_xL1xR1	Location of maximum distortion of first half wave on left & right side of weld seam varied

The variable parameters in the half-half wave series and the range of their magnitudes being varied are presented in Table 3 below. See Figure 7 for better understanding of the distortion parameters and their locations.

Table 3.Variable distortion parameters in half-half wave series.

Variable parameters	Range of varied magnitude
δ	-4 mm, -3 mm, -2 mm …9 mm
x_{L1}	50 mm, 100 mm, 150 mm ...1000 mm
x_{R1}	50 mm, 100 mm, 150 mm ...1000 mm
δ_{L1}	-6 mm, -5 mm, -4 mm …9 mm
δ_{R1}	-6 mm, -5 mm, -4 mm …9 mm
α	measured from the 3D model after it is created

The origin for the magnitude of the variables are the X-axis and Y-axis on Figure 7.

2.2 *Full-full wave family*

The distorted models of the full-full wave family were divided into five series as it was in the half-half wave family. The series are tabulated below in Table 4 and the range of magnitudes for variable parameters of full-full wave series are in Table 5.

Table 4. Full-full wave family series.

half-half wave series	Description
202_δ	Lateral distortion (δ) varied
202_δL1δR1	Maximum distortion of the first half wave on left and right side of weld seam varied
202_δL2δR2	Maximum distortion of the second half wave on left and right side of weld seam varied
202_xL1xR1	Location of maximum distortion of first half wave on left & right side of weld seam varied
202_xL2xR2	Location of maximum distortion of second half wave on left & right side of weld seam varied

Table 5. Variable distortion parameters in full-full wave series.

Variable parameters	Range of varied magnitude
δ	-5 mm, -4 mm, -3 mm …4 mm
$x_{L1} = x_{R1}$	50 mm, 100 mm, 150 mm ...400 mm
$x_{L2} = x_{R2}$	200 mm, 300 mm, 400 mm ...1000 mm
$\delta_{L1} = \delta_{R1}$	-5 mm, -4 mm, -3 mm …4 mm
$\delta_{L2} = \delta_{R2}$	-5 mm, -4 mm, -3 mm …7 mm
α	measured from the 3D model after it is created

2.3 *Measuring the angle of distortion*

In flat plates, angular misalignment can be measured following the definitions in IIW and other standards, but the methods to measure it in distorted or curved plates had not been established yet. Due to the curvature near butt weld, the estimation of distortion angle is very sensitive to the location of reference points. In order to assure unambiguous estimation of the angle from all the panels, a simple rule to measure the distortion angle was established as explained in Figure 8. The distance of reference lines from the weld seam were simplified as such to account the variation of maximum distortion location in different models. The local angular misalignment in then calculated as:

$$\alpha\,[°] = 180° - \mathit{Measured\ distortion\ angle}\,[°] \qquad (7)$$

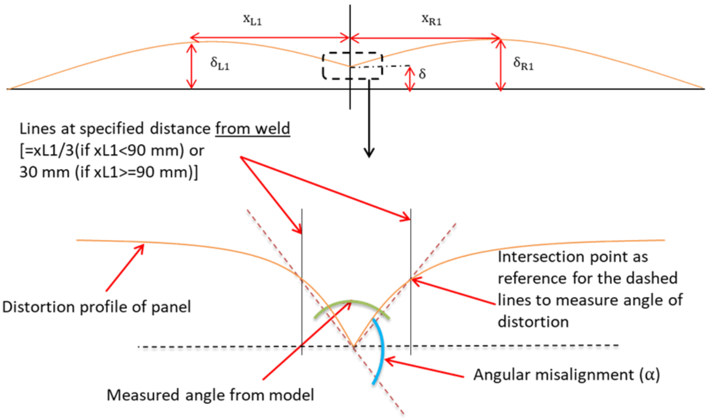


Figure 8. Measurement method for local angular misalignment.

2.4 *FEA model*

Ship deck panel has two stiffeners and two T-girders welded to 4 mm thick deck plating. Laser-hybrid butt weld was applied on the deck plating. Two stiffners (HP80x5) with 404 mm spacing, and T-girders (T440x7/150x10) with 2560mm spacing were welded to the deck plating (Lillemäe-Avi et al 2017).

The control curves for distorted 4 mm plate were created using B-splines in CREO 3.0 software. The 3D geometry of the plate was prepared with control curves and straight boundaries. It was imported to FEMAP v11.3 for FEA. A frame was created in FEMAP with stiffeners and T-girders to provide realistic boundary conditions for the distorted butt-welded thin plate as shown in Figure 9. The frame was constrained to duplicate the experimental boundary conditions of Lillemäe et al (2017). The cross-section at one end of the frame was fixed, i.e. Tx, Ty, Tz, Rx, Ry, & Rz = 0. The other end was constrained with one DOF, i.e. Tx, Tz, Rx, Ry, Rz = 0, & Ty ≠ 0. A properly distributed tensile load of 620 kN was applied on the translating end. The remaining edge were free.

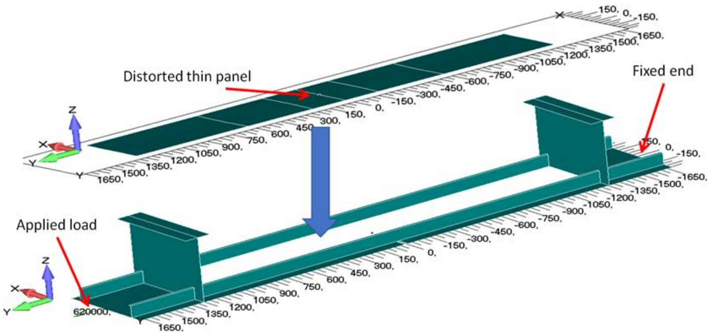


Figure 9. Model of distorted panel and frame for FEA.

Shell elements with four nodes, steel material with Young's Modulus 206.8 GPa, and Poisson's Ratio of 0.3 were used in FEA model. The thickness increase due to welding is assumed symmetric with respect to the midplane of the panel, and the elements at butt weld were thickened to imitate the additional stiffness as in Lillemäe-Avi et al (2017). The mesh on the distorted plate is shown in Figure 10.

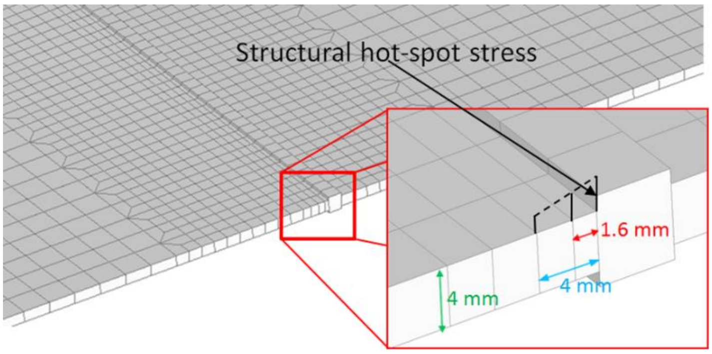


Figure 10. Mesh near the butt weld in distorted plate model.

2.5 *Method validation*

The modelling of distorted welded plate was validated with experimental data and higher accuracy models from Lillemäe et al (2017). The geometry of distorted 3D model was validated with the optically measured deck panel from Lillemäe et al (2017). The FEA results were validated with results from Lillemäe et al (2017) and a 9.26% difference was observed in maximum stress near the butt weld on top surface of distorted plate. Contour plots of the comparison from top surface of the butt-welded 4 mm thick distorted plates is shown in Figure 11.

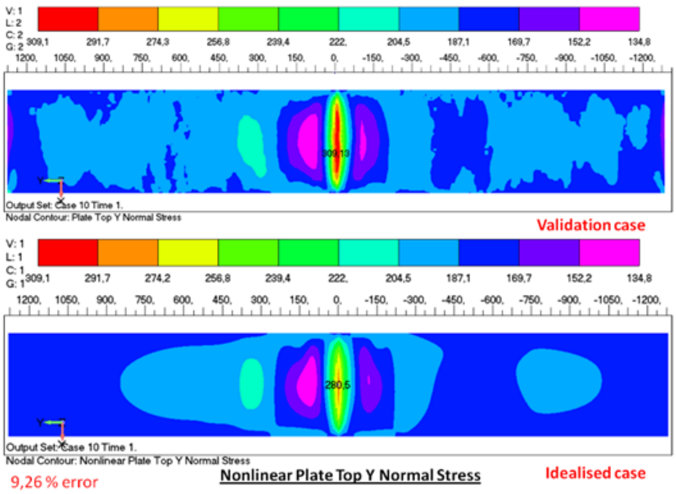


Figure 11. The contour plots of nonlinear plate top normal stresses of experimental and modelled distorted panels.

3 RESULTS

The distortion models of half-half and full-full wave series were analyzed and stress magnification factors were calculated. k_m was plotted against the distortion parameter and local angular misalignment. FEA results are compared with analytical solutions of IIW and the most significant results are presented below.

3.1 *Influence of distortion magnitude*

The k_m showed a drastic increase with the increase in distortions near butt weld. The largest distortions on first half-wave from the weld seam (δL1 & δR1) posed a significant influence on k_m when they were close to the weld seam as shown in Figure 12. However, the distortion parameters of second half-wave from the weld seam (δL2, δR2, xL2 & xR2) did not significantly influence k_m at the butt weld as shown in Figure 13. The distortions on first half-waves near the butt weld were responsible to increase the angle of distortion creating a sharp change in geometry. It created high stress concentration near the butt weld and increase k_m. On the other hand, distortion at second half-wave far from the butt weld had a minor effect on geometrical changes near the butt weld resulting in almost no impact on k_m at butt weld.

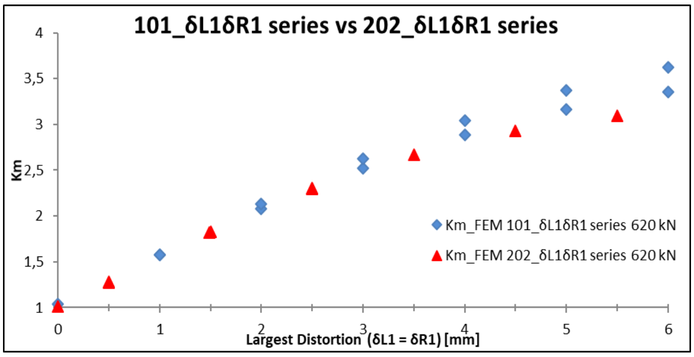


Figure 12. Influence of distortion on the first half-wave from butt weld, δ_{L1} & δ_{R1} varied keeping other parameters constant.

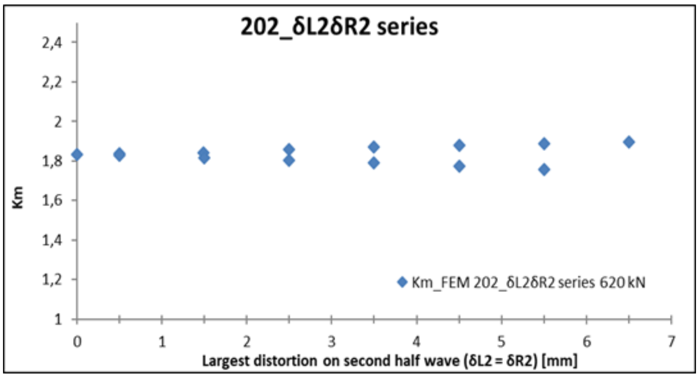


Figure 13. Influence of distortion on the second half-wave from butt weld, δ_{L2} & δ_{R2} varied keeping other parameters constant.

Likewise, the lateral distortion of weld seam demonstrated a high influence on k_m at the butt weld. There was a large scatter between the results of half-half and full-full wave series when k_m was compared with respect to the distortion parameter as shown in Figure 14. However, when the same results were compared with respect to local angular misalignment, the scatter was significantly reduced as shown in Figure 15.

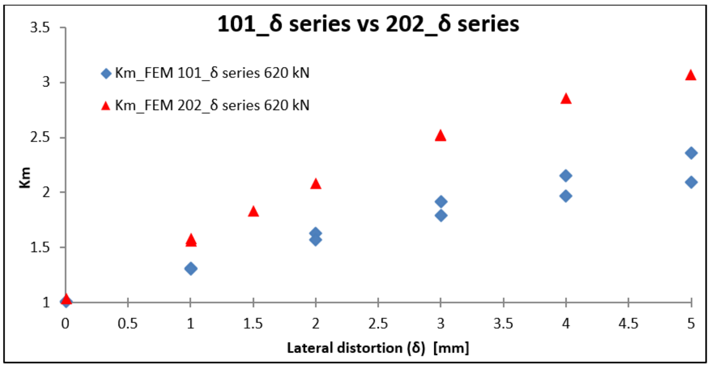


Figure 14. Stress magnification factor vs lateral distortion of weld seam in full-full and half-half wave models.

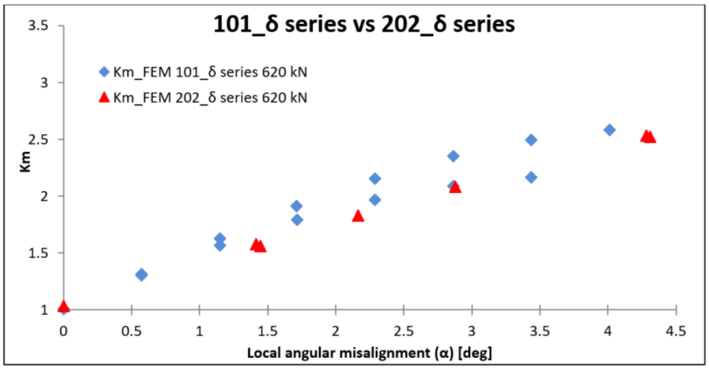


Figure 15. Stress magnification factor vs local angular misalignment at weld seam in full-full and half-half wave models.

3.2 *Influence of location of maximum distortion*

Similar to the magnitude of distortion, the location of maximum distortion had a strong influence on the stress magnification factor when it was near the butt weld. Figure 16 demonstrated the decreasing stress magnification factor as the distance of the maximum distortion increases from the butt weld.

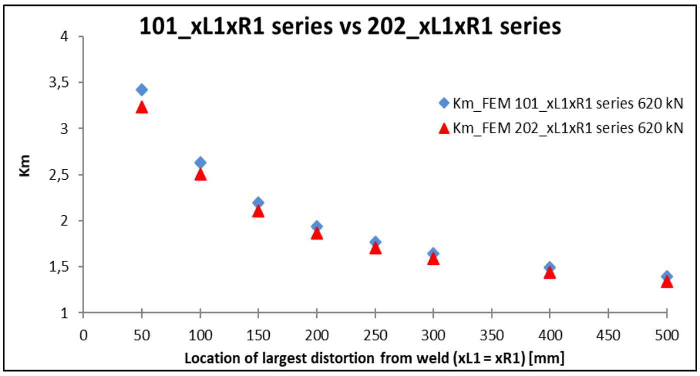


Figure 16. Influence of location of maximum distortion on the first half-wave from the butt weld.

On the other hand, the location of maximum distortion of the half-wave profiles away from the butt weld does not show any impact on the stress magnification factor at the butt weld as shown in Figure

17. However, it was observed that when the location of maximum distortion on the half-waves further away from the butt weld approach the fillet welds on the boundaries, it tends to increase stress there.

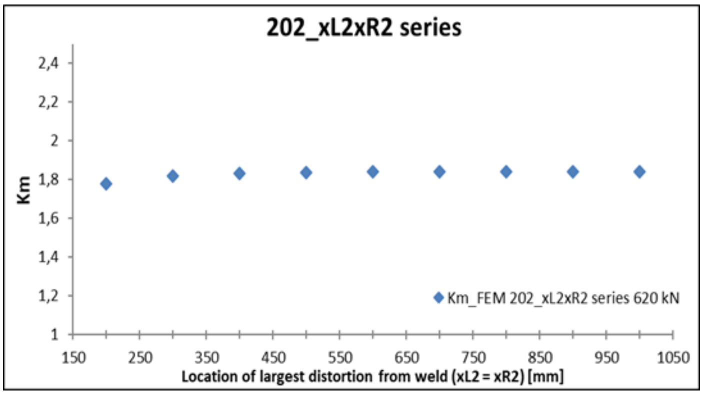


Figure 17. Influence of location of maximum distortion on the second half-wave from the butt weld.

3.3 *Influence of local angular misalignment and number of waves of distortion*

The above-mentioned distortion parameters show a significant impact on k_m when they are close to butt weld, but the results are different when they are further away. However, with respect to the local angular misalignment, the influence of shape and location are minimal. The results presented in Figure 18 and Figure 19 are collected from all the simulated models of distortions. They show a consistent trend of k_m development with the increase in local angular misalignment irrespective to the shape of distortion or other distortion parameters. The respective results from the analytical equations of IIW gives linear results and different slopes for different load levels as shown in Figure 18 and Figure 19. It underestimates k_m at lower local angular misalignment and highly overestimate it at higher local angular misalignment.

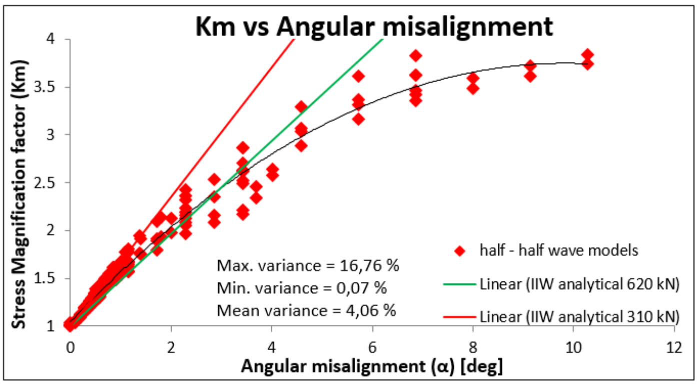


Figure 18. Stress magnification factor vs local angular misalignment in half-half wave models.

Increase in number of waves of distortion shows a slight decline in k_m with respect to local angular misalignment as shown in the Figure 18 and Figure 19. The number of waves on the distorted plate has a minor influence at lower local angular misalignments, but the influence of number of waves increases with increase in local angular misalignment.

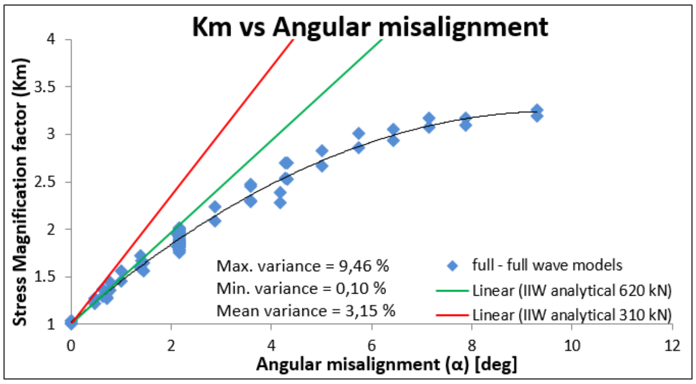


Figure 19. Stress magnification factor vs local angular misalignment in full-full wave models.

4 DISCUSSION

The results demonstrate that the geometrical imperfections, such as local angular misalignment, and distortions have a significant effect on the stress development in the distorted panel, this is in good agreement with previous research (Lillemäe et al 2012, Remes & Fricke 2014, Remes et al 2017). Largest stresses were observed in the butt weld, and the boundaries demonstrated higher stresses compared to other areas in the plate. The redistribution of stresses in the distorted panels caused an increased stress in the boundaries as explained by Eggert et al (2012). In the FEA of the distorted deck panels, larger magnitude of distortion parameters (δL1, δR1, δL2 and δR2) caused higher stress accumulation in their vicinity around the boundaries of the distorted plates; this is in well agreement with the findings from previous research (Eggert et al 2012, Fricke & Feltz 2013).

Among the studied distortion parameters, the most influential parameter was found to be the local angular misalignment, followed by the magnitude of the lateral distortion of the weld seam. In the research by Eggert et al, it was discussed that a roof-like appearance with large angular misalignment in weld joint caused highest stress magnification (Eggert et al 2012). The results of this paper support that observation. As the local angular misalignment grows, from zero to ten degrees, there was a sharp increase in the stress magnification factor as shown in Figure 18 and Figure 19. The roof-shape distortions similar to that mentioned in previous research was found among the 3D models of distorted panels with large local angular misalignments.

The magnitude of distortion from the first half-wave from the weld seam (δL1 and δR1) posed a significant influence when the locations of highest distortion (xL1 and xR1) were close to the weld seam. Such a combination had a high effect on increasing the local angular misalignment. However, the distortion parameters of the second half-wave from the weld seam (δL2, δR2, xL2 and xR2) had a minor impact on the stress magnification factor as it had almost no effect on the local angular misalignment at the butt weld

The increase in load intensifies the straightening effect in a distorted panel, therefore a consistent gradual decline of k_m at the butt-weld was observed with the increase in tensile load as observed in previous research (Eggert et al 2012, Lillemäe et al 2016, Kuriyama et al 1971). The straightening effect was observed slightly larger in full-full wave models compared to corresponding half-half wave models. However, the load level does not have a big influence in the stress magnification of distorted panels.

The number of half-waves (or the shape of distortion) in the distorted panels shows an influence on k_m as can be seen in Figure 18 and Figure 19. The stress magnification factor shows a noticeable drop as the number of such half-waves increases in the distorted models with respect to the local angular misalignment. The influence of number of waves, however, is prominent only in larger local angular misalignments, while the shape of distortion has smaller influence at smaller local angular misalignments as shown in Figure 18 and Figure 19.

Unlike the local angular misalignment, distortion parameters such as δ, δL1, δR1, xL1, & xR1 cannot individually provide a consistent estimation of the k_m in distorted models with different shapes. IACS and other standards only provide the limit for one individual distortion parameter of distorted panels. Such individual distortion parameters are sensitive to the location of distortion and shape of distortion. Some of the modelled panels in this research developed alarming stress magnification factor even within the limits of distortion set by IACS due to the influence of shape of distortion. This is in well agreement with the findings of Lillemäe et al, where the shape of distortion was deemed more important than the magnitude (Lillemäe et al 2016). However, if the limits were observed with respect to the local angular misalignment, the shape would have less influence on the stress magnification factor. Therefore, it is more advisable to have the limits set with respect to the local angular misalignments.

The current rules of IIW and classification societies are based on a linear relationship between angular misalignment and the resulting k_m. The relation, however, has been observed to be non-linear in this research as well as in other previous research due to straightening effect and geometrical non-linearity. The straightening effect has been taken into consideration in IIW rules with a tanh correction factor based on an assumption that the initial misalignments are on an ideally undistorted plates, which is not true in case of thin welded panels (Kuriyama et al. 1971). Even with the correction factor, the rules are still linear and cannot predict the stress magnification factors for the distorted panels as modelled in this research. Furthermore, the non-linear behavior of the structure due to the distortions has not been included yet. The results of this paper show that the linear analytical solutions from IIW underestimate the stress magnification factor at low magnitudes of local angular misalignment. However, when local angular misalignment grows, the analytical solution of IIW highly overestimates the stress magnification factor as shown in Figure 18 and Figure 19.

5 CONCLUSION

Among numerous possibilities of distortions, the research focused on two types (families) of distortions: half-half wave models and full-full wave models. The One-at-a-time (OAT) sensitivity analysis method was implemented with 10 different series of modelled distorted deck panels to understand the effect of distortion parameters on stress magnification factor, and to distinguish the most influential parameter among them. The resulting stress magnification factors were compared against distortion parameters as well as local angular misalignment and following findings were obtained:

- The magnitude of distortions of the first half-wave from the weld seam (δL1 and δR1) posed a significant influence on k_m when the locations of highest distortion (xL1 and xR1) were close to the weld seam. However, the distortion parameters from the second half-wave from the weld seam (δL2, δR2, xL2 and xR2) did not pose significant influence on the k_m at the butt weld.
- The distortion parameters such as δ, δL1, δR1, xL1, and xR1 cannot individually provide a consistent estimation of the stress magnification factor in the distorted models, and these individual parameters are sensitive to the shape of distortion. Therefore, it is more advisable to have the limits set with respect to the local angular misalignments instead of global distortion.
- The most influential distortion parameter was found to be the local angular misalignment, followed by the magnitude of the lateral distortion of the weld seam. The stress magnification factor shows a noticeable drop with respect to the local angular misalignment as the number of half-waves increases in the distorted models. The influence of number of waves, however, is prominent only in larger local angular misalignments, while the shape of distortion has smaller influence at smaller local angular misalignments.

6 RECOMMENDATIONS FOR FUTURE WORK

In this study, the sensitivity analysis was simplified by considering only one parameter at a time without the consideration of axial misalignment. Therefore, future works should include the study of possible interactions among the all distortion parameters as well as other possible distortion shape in order to cover different manufacturing processes used in shipyard production. Furthermore, this study focused on butt-welded joints, which was the most fatigue critical in the full-scale panel test. However, in the case of a low local angular misalignment at butt joint, the fillet welds along stiffeners and T-girders can become fatigue critical. Thus, future works should also cover fillet welded joints and other possible loading cases.

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