The Influence of Geometrical and Welding Imperfections on the Strength of Stiffened Structures

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Abstract. *The topic of this article is the application of an analytical numerical hybrid model for a realistic prediction of imperfections induced by welds. At the beginning, the analytical model, its physical basis as well as the physical interrelationships are explained. This is followed by the explanation of the coupling procedure between the analytical model and the numerical calculation. The significance of the hybrid model is proven by means of a few sample applications. Afterwards, the coupled hybrid model is applied on the investigated stiffened structure for the determination of the weld imperfections. An ultimate load analysis gives information about the load carrying behaviour under axial loading. The results are compared with the results of an ultimate load analysis from a literature example assuming different eigenvalues with different scaling. The comparison underlines the potential additional utilization of load bearing capacity by this new approach.*

1 INTRODUCTION

The strength calculation of stiffened plates by the finite element method (FEM) has been part of the state of the art for a long time. Geometrical nonlinearities as well as the nonlinear material behaviour are considered within the calculation. To simplify, both types of imperfections, geometrical and structural ones, are mostly combined in these strength calculations being considered as equivalent geometrical imperfections. Values for standard cases are included in EN 1993-1-5 in case of plated structures [1]. Additionally, global and local imperfections are distinguished. The global imperfections can be defined as a bending of the whole structure with a maximum depending on its dimensions. The local imperfections are mostly determined through a numerical eigenvalue analysis. The challenge of a numerical ultimate load analysis is the detection of the lowest ultimate load by the combination of different imperfections. Numerous research work deals with the numerical load capacity calculation of stiffened plates and [2-5]. However, it remains unclear to some extend how accurate these geometrical imperfections represent the actual residual stresses and deformations caused by welds, especially for more complex cases. The significance of numerical load capacity calculations could be increased enormously if these imperfections are known more exactly and could be considered directly during the computation.

Nowadays, the residual stresses and deformations can be determined by means of a thermo-mechanical FE-simulation. This approach contains two steps: the calculation of the transient temperature field followed by the calculation of the mechanics. These simulations can be used to calculate very realistic values. However, the effort for the calibration and validation of the simulation is huge and temperature-dependant thermophysical und thermomechanical material properties are required. In addition, relevant structures and weld length are very large what leads to enormous calculation time and a huge demand of storage capacity [6]. Simplified numerical approaches are available and able to remedy this situation. However, the application of these models partly demands more expertise than a conventional thermomechanical FE calculation [7] or the simplifications are so extensive that the weld imperfections calculated by the approach partially loses their validity [8].

Knowing the imperfections caused by welds is not only important for strength calculations but also for the proper functioning of the manufacturing process. For that reason, research and development started working on analytical approaches already in the 50's [9]. Especially the semi-empirical shrinkage force model has proven its good validity [10, 11]. The area of application covers several types of joints, various steel grades and aluminium alloys as well as different welding techniques. Moreover, the influence of the weld parameters, material properties, phase transformation, the stiffness of the structure and clamping conditions are captured within the calculation [12]. Nevertheless, its application is limited to simple weld structures and constant cross sections along the weld. For calculating large realistic structures with varying complex geometries and lots of welds the straight analytical approach is not suitable.

In order to be able to take weld distortions and residual stresses directly into account in a load capacity calculation, fast but still sufficiently accurate procedures that, at the same time, are easy in its application are essential. The coupling of an analytical model and a FE simulation could meet these requirements. In [13] a procedure is proposed considering the stiffness and the maximum temperatures when calculating the inherent strains in longitudinal and transversal direction analytically in a cross section. For determining the weld distortions, the strains are applied to the FE model by extrusion alongside the weld followed by an elastic analysis. The results of the application of the inherent strain model showed good agreement with experimental data [14]. However, there is no approach suggested for the precise calculation and consideration of the stiffness. It is approximated exclusively by means of experience. The realization of an analytical numerical model that links the shrinkage force model as mentioned above with the FE calculation enables a much wider application range and the consideration of further significant influences on weld imperfections [15].

2 THE COUPLED ANALYTICAL NUMERICAL HYBRID MODEL

The basic idea of the coupled analytical numerical shrinkage force model is the linking of the major advantages of both, analytical and numerical procedures. On the one hand, the matchless marginal calculation time of the analytical shrinkage force model and its simple application, and on the other hand the possibility to conduct a FE simulation to calculate stresses and distortions at any location of complex welded structures. According to this, all the determining factors on quality and quantity of weld imperfections are passed to an analytical calculation program, capturing the mathematical approach of the shrinkage force model. The output is a mechanical load and the point of action in longitudinal and transversal direction, equivalent to the heat effect of welding. The loads are then applied to the finite element model of the weld structure and the distortions and stresses are calculated by an elastic calculation. The influence of the weld sequence on the arising weld imperfections is captured by a back coupling. The numerically calculated stresses in the regarded weld caused from a previous weld are submitted to the analytical calculation. The complete scheme is shown in fig. 1.

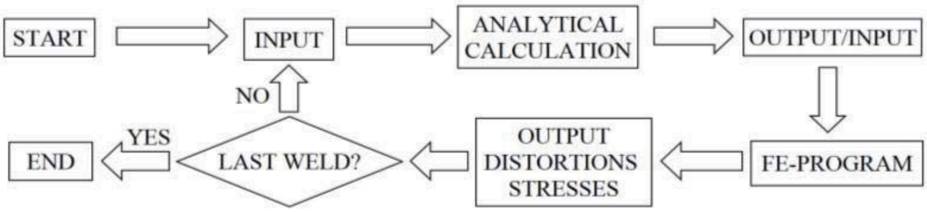

Figure 1: Schedule of the coupled analytical numerical hybrid model.

2.1 The analytical shrinkage force model

Weld imperfections depend significantly on the maximum temperatures that every point vertical to the weld direction is exposed to and the stiffness of the structure. Equations for the calculation of the maximum temperatures were derived by Rykalin [16] constituting the basis of the shrinkage force model. Two border cases are considered: a line source in a thin plate with isotherms penetrating the plate and a point source on a semi-infinite body with circular isotherms around the weld. The proportion of each of the two border cases to the resulting temperature field in the investigated weld structure depends on the heat input per unit length, the geometrical properties as well as the heat exchange with the environment and is calculated iteratively. Considering further influencing factors, an axial force F_x is calculated equalling to the heat effect of welding [12]:

$$F_x = 0{,}355\frac{\alpha}{c\rho} q_s E K_{\chi\delta} K_k K_\sigma, \tag{1}$$

with the thermal expansion coefficient α, the specific heat capacity c, the density ρ and the Young's modulus E. $K_{\chi\delta}$, K_k and K_σ are capturing the temperature field in medium thick plates, the stiffness of the weld structure and the effect of existing stresses in the weld. Furthermore the transversal shrinkage force F_y is calculated as follows:

$$\begin{aligned} F_y &= q_s \frac{\alpha}{c\rho} E\left[0{,}255 + 0{,}745 K_\delta \left(0{,}04 + 0{,}96 K_{av}\right)\right]\left(1 + K_\mu K_\delta\right)\times \\ &\times\left[1 + K_C(1+K_\delta)\right] K_W K_\delta + q_s \frac{\varepsilon_F}{\theta}\left(1 - K_\delta\right), \end{aligned} \tag{2}$$

where K_δ captures the degree of heating through the thickness, K_{av} captures the influence of stiffening cross-beams, K_μ determines the effect of longitudinal strains on the plastic transversal strains, K_c is the degree of excessive heat and K_w captures the effect of forced heat exchange. ε_F is the yield strain and θ is the proportionality factor between the heat input per unit length and the cross section of the weld. The axial shrinkage force F_x, eq. 1, is proportional to the width of the plastic zone:

$$b_{PZ} = \frac{F_x}{\varepsilon_m E \delta}. \tag{3}$$

Here, ε_m is the averaged yield strain and δ is the plate thickness. The appropriate points of action z_c are equal to the centre of the zone of plastic deformations. They are significantly influenced by the material and its properties as well as the heat input per unit length and the plate thickness. Depending on the points of action a equivalent linear strain distribution or respectively stress distribution over the plates thickness can be calculated. Considering the point of origin in the centre of gravity of the plates cross section, the strain distribution $\varepsilon(z)$ follows as:

$$\varepsilon(z) = \varepsilon_m + \frac{12\varepsilon_m z_c}{\delta^2} z. \tag{4}$$

2.2 The coupling procedure

For the coupling of the analytical shrinkage force model with the FE simulation different mechanical loads are available. The deformation state calculated by applying loads and appropriate points of actions or alternatively eccentric pressures matches well with experimental results. However, the calculated stress state in the structure is qualitative wrong. Instead, specifying strains or stresses linear distributed over the plates thicknesses, fig 2, leads to correct stresses with tension in the weld and balancing compressive stresses in the nearby regions. The procedure is already validated and verified with Ansys®, LS Dyna®,Sysweld® and Abaqus®. When loading the FE model with stresses σ the Poisson's ratio ν must be considered:

$$\sigma_{x,y} = \frac{\varepsilon_{x,y} E + \varepsilon_{y,x} E \nu}{1-\nu^2} \tag{5}$$

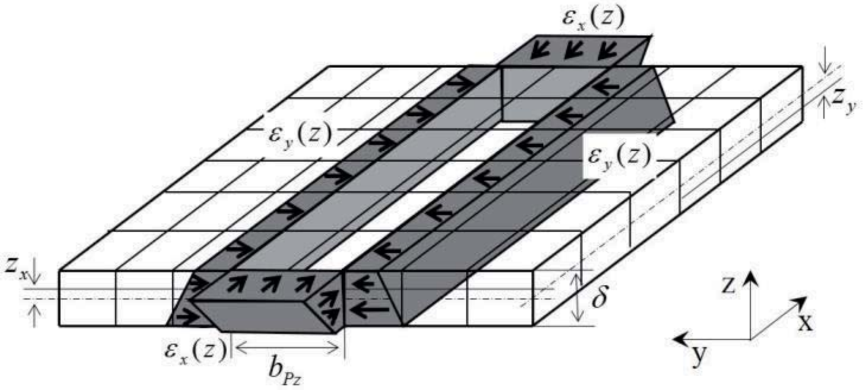

Figure 2: Coupling by means of linearly distributed strains [15]

2.3 Application of the hybrid model on a large welded structure

The hybrid model for calculating weld imperfections, mostly distortions, was validated by means of numerous experimental welded butt and T-joints. The geometry, the material as well as the welding technique and welding parameters were varied during the experimental studies. The calculated distortions in the longitudinal and transversal direction as well as the bending and the angular distortions always showed a very good agreement with the measured data.

Thereafter, the shrinkage force model was applied on a deck section from ship building, fig 3(a). Walls and smaller parts as well as different stiffened parts like stringers and deck beams are welded with approximately 90 fillet welds on a 20x16 m large base plate. The welding technique is MAG and laser MAG hybrid welding and the material grade is GL-A36 (S355J2H). Simplifying, the thickness of the stringers in the FE model is reduced according to the perforation, fig 3(b).

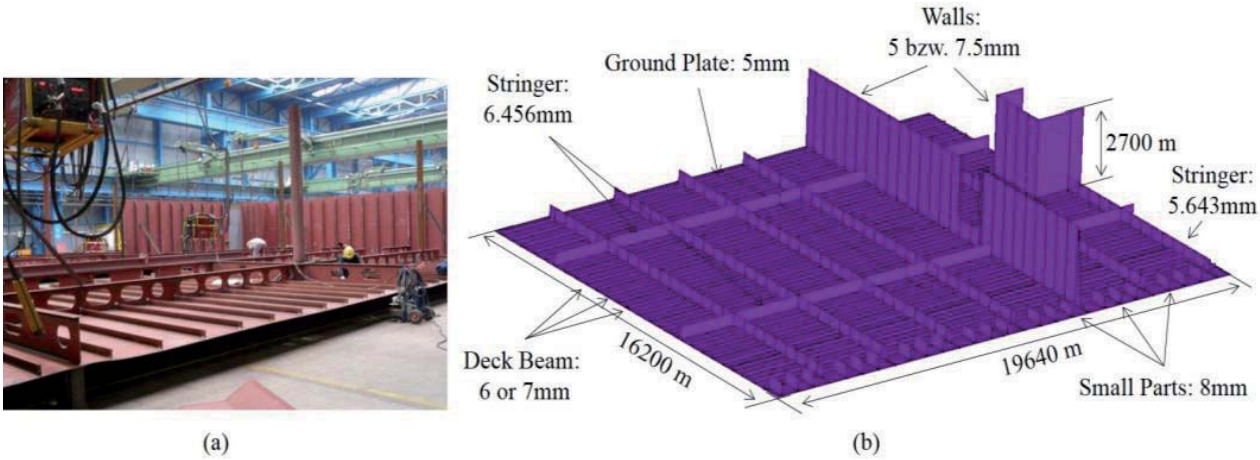

Figure 3: The deck section (a) the dimensions and the nomenclature (b).

The manufacturing process is subdivided into three steps. First, 24 deck beams are welded with laser MAG hybrid welding on the base plate. Afterwards, seven stringers are assembled using semi-automated MAG welding. At the end four large walls and the small parts are joined on the base plate using the same welding technique like in the manufacturing step before, fig 4(a). The weld distortions are compared with measurements taken after each manufacturing step alongside six paths in longitudinal and nine paths in the transversal direction, fig 4(b). These measurements were done at a total of three deck sections.

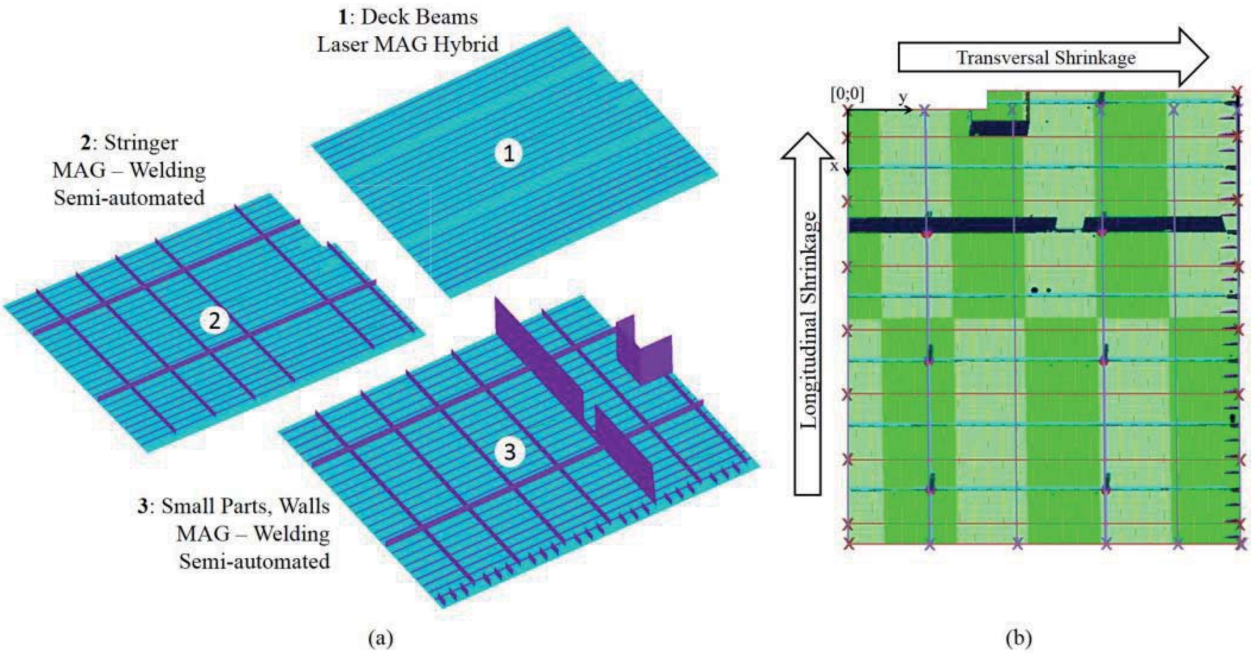

Figure 4: The three manufacturing steps (a); measuring paths in longitudinal and transversal direction (b).

The structure under investigation is almost symmetrical and thus the welding of each single beam as well as each single stringer has a similar effect on the measured welding distortions in longitudinal and transversal direction. Therefor the results of the experiments and the hybrid calculation at each single path are summarised in scatter bands, fig 5. Apart from the calculated transversal distortion in manufacturing step 1 the results show a pretty good agreement.

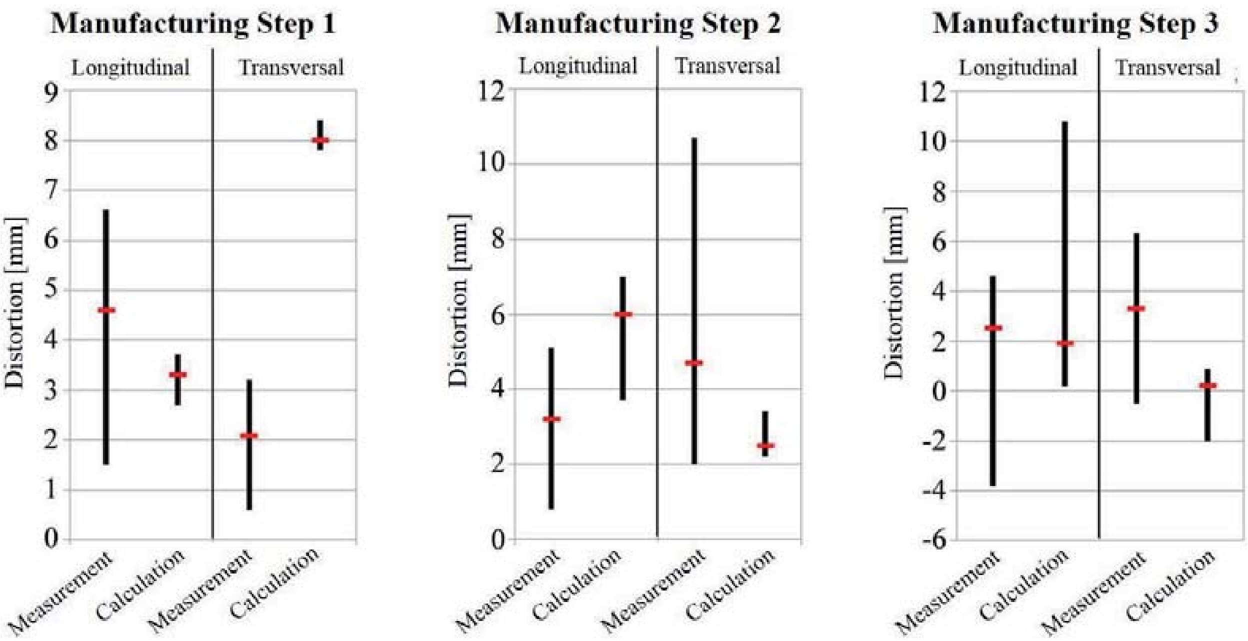

Figure 5: Scatter bands of the experimental measurements compared with the calculations.

3 THE FINITE ELEMENT MODEL OF STIFFENED STRUCTURE

For the application of the analytical numerical hybrid model and a subsequent load capacity calculation a structure was chosen consisting of a base plate and two welded stiffeners. The first six buckling modes as well as the corresponding load deformation curves considering different imperfection states were already determined in [2]. For the verification of the boundary conditions of the FE model to be used, the eccentricity of the load application point and the geometrical properties were varied in order to recalculate the buckling modes and the corresponding stresses as exactly as possible using shell elements of the type that was used in [2]. Targeting the simplest application of the hybrid model with Abaqus® CAE, afterwards, the numerical calculations were repeated using quadratic 3D-elements type C3D20 with an element edge length of 25 mm, fig 6.

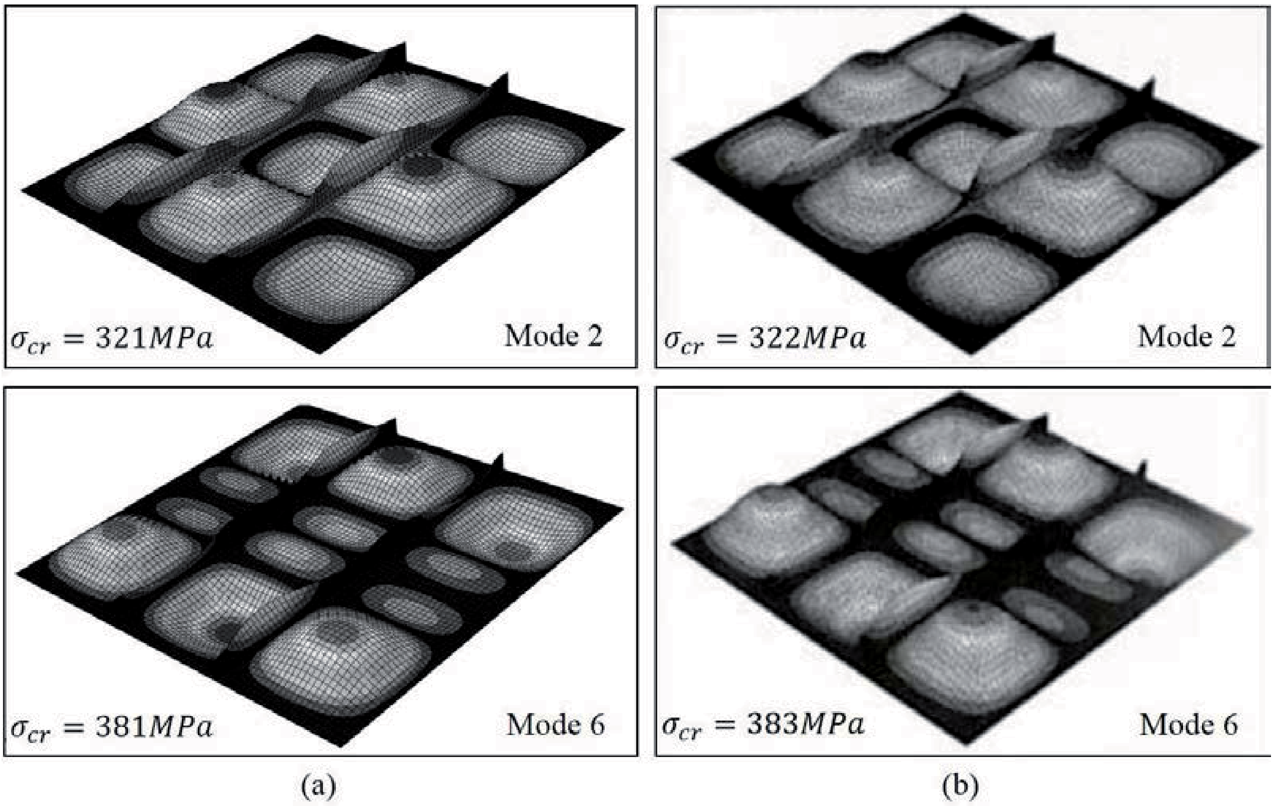

Figure 6: Verification of the FE model by comparing second and sixth buckling mode and corresponding stresses of the numerical simulation with 3D-elements (a) with the data taken from literature [2] (b).

The first and second buckling modes were used for a subsequent load deformation analysis considering these as geometrically equivalent imperfections. According to EN 1993-1-5 [1], the global buckling mode one was scaled to 4.5 mm while the local buckles of buckling mode were assigned a maximum of 3 mm. The comparison of the calculated load deformation behaviour with the load deformation curves given in the literature [2] shows consistency, fig 7(a). However, it turned out that the height of the stiffeners, differing from the declaration in [2], is 94 mm and the force application point *AP* is 2.3 mm above the centre of gravity of the ground plates cross section, fig 7(b). The load application as well as the bearing in longitudinal direction is realized via “kinematic coupling”, so that the cross sections can distort but not warp. A bilinear elastic plastic material behaviour was chosen with a yield point of 355 MPa. Via true strain and logarithmic strains, the strain hardening was modelled.

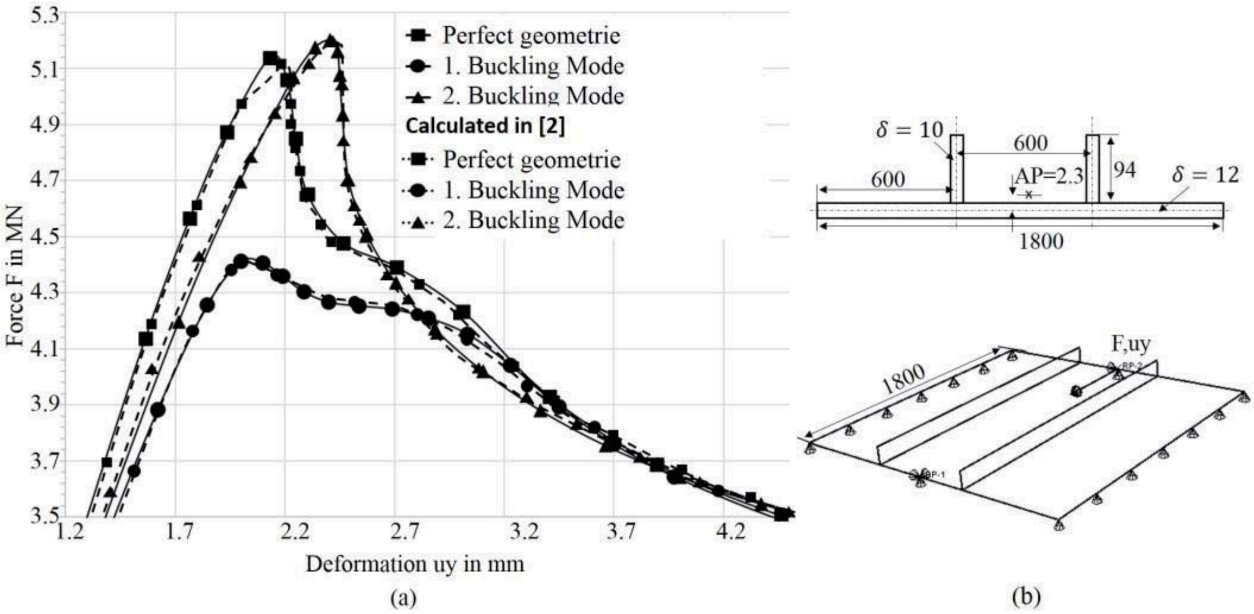

Figure 7: Comparison of the calculated load deformation curves with the literature [2] (a); geometrical properties and boundary conditions of the finite element model (b).

4 APPLICATION AND RESULTS OF THE ANALYTICAL NUMERICAL HYBRID MODEL FOR CALCULATING WELD IMPERFECTIONS

The requirements for the calculation of the mechanical loads with the analytical shrinkage force model are information about the type of joint and its dimensions, the material data as well as the welding technique and the welding parameters. The geometrical properties are shown in fig 7(b). Here, the assumption is made that the stiffeners are welded one sided, each on the outer side. Material data, such as thermal conductivity, thermal expansion coefficient, density etc. correspond to the material data of the steel S355J2H. The weld technique is conventional MAG-welding with welding parameters targeting a fillet weld with a design throat thickness of approximately 7 mm, which resulted in a heat input per unit length of q_s=1675 J/mm. In this case, the linking between the analytical model and the numerical approach was done by initial stresses, table 1. Due to the effects of lateral contraction, these stresses must be calculated considering the Poisson's ratio, eq. 5.

Table 1: Analytically calculated stresses for the numerical calculation of geometrical and structural weld imperfections.

	Plate		Stiffener	
	Upper Side	Lower Side	Upper Side	Lower Side
Width of Plastic Zone b_{pz} in mm	23,2		23,2	
Stresses in Weld Direction σ_x in MPa	712	459	727	439
Stresses Transversal to the Weld σ in MPa	σ_y=1031	σ_y=491	σ_z=1014	σ_z=493

For the proper loading of the FE model, six sections were created at each weld, representing the idealised zone of plastic deformations, fig 8(a). The height of every single section is equal to the half of the plate thickness respectively the thickness of the stiffener. The width of the sections is specified by the width of the analytically calculated zone of plastic deformations. When creating the sections, the position of the welds on the outside of the stiffeners is considered, fig 8(b).

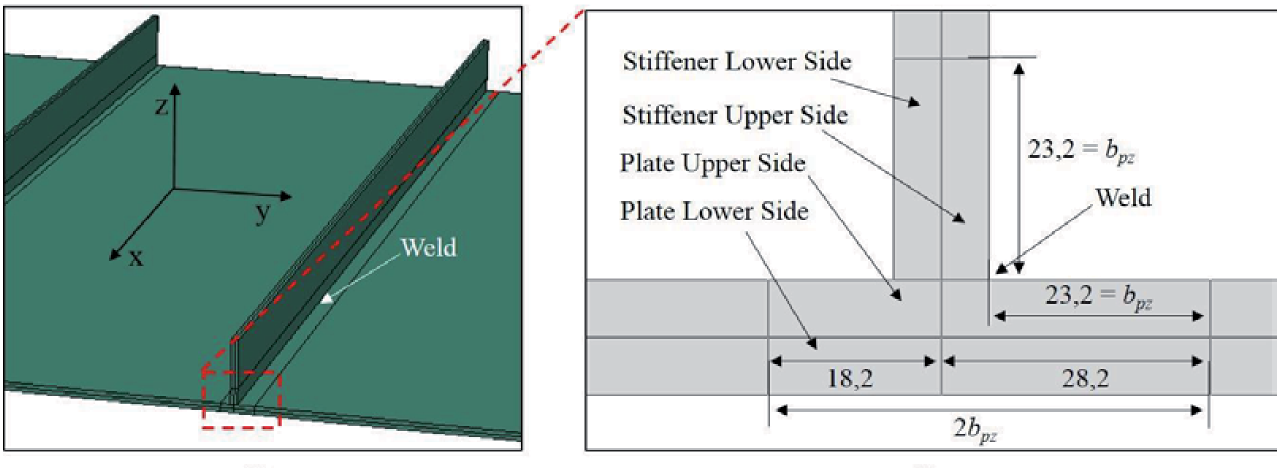

Figure 8: Assembly of the FE-Model in the region of the welds (a) and declaration and dimensions of the sections (b).

The initial stresses in longitudinal and transversal direction are defined as “initial state” in Abaqus®. Geometric nonlinear behaviour is considered within the elastic calculation. The calculated deformation state indicates buckling of the unstiffened areas in the positive z-direction, fig 9(a), and a tilt over of the stiffeners towards the welds, fig 9(b). The results of the hybrid calculation correlate with empirical values. Since the boundary conditions “kinematic coupling” at the locations x=0 and x=1800 mm are kept during the calculation, the deformations are slight in general.

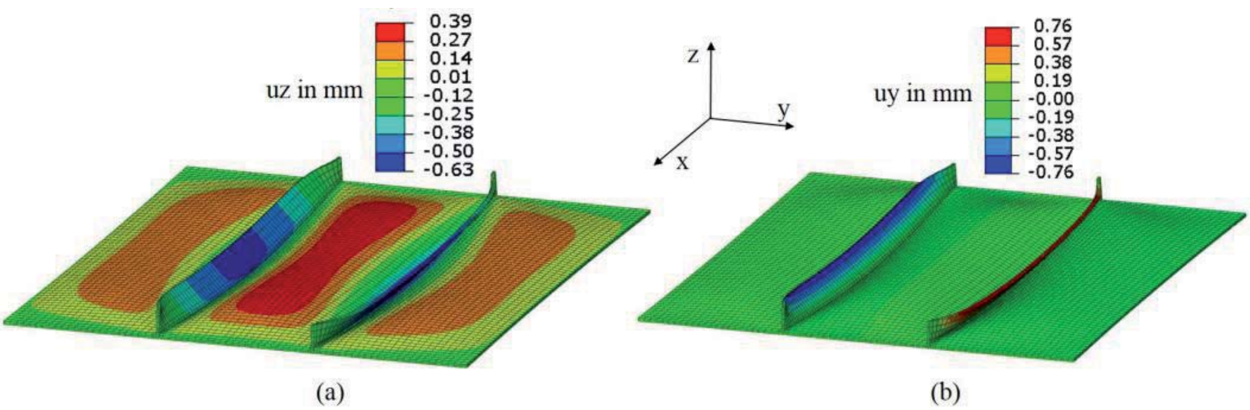

Figure 9: Buckling of the unstiffened areas in the positive z-direction (a) and tilt over of the stiffeners in positive and negative y-direction (b)

5 RESULTS OF THE LOAD CAPACITY CALCULATION

For the evaluation of the potential of the calculation of realistic weld imperfections and a subsequent load capacity calculation two border cases are considered. The first one is a combination of the first buckling mode scaled to 4.5 mm and the calculated weld imperfections. This is a very conservative assumption, because the used magnitude of the first buckling mode already includes the weld imperfections as well as fabrication tolerances and manufacturing failures. In the second case, all imperfections in the structure are caused only by the two welds. Thus, the initial state of the structure for the load capacity calculation is the result of the application of the hybrid model to an ideal model. The comparison of the results is done by the means of the calculated load deformation curves. The achieved results using the two defined border cases are compared against the original load deformation curve of this example.

The calculated ultimate load of the structure assuming the imperfections according to the conservative first border case increases by about 7 %. Basic cause for that is the weld induced bending of the stiffeners, fig 9 (a), contrary to the failure of the structure, fig 10. Hence, it acts stiffening in this specific case. In most cases, weld imperfections are dominating the imperfection level of a welded structure. Therefore, the second regarded border case is a load capacity analysis of the structure considering only the weld imperfections. The result is an increasing of the ultimate load by about 21 %, fig 10. The reality will be somewhere in between, since small fabrication and manufacturing failures will also influence the results.

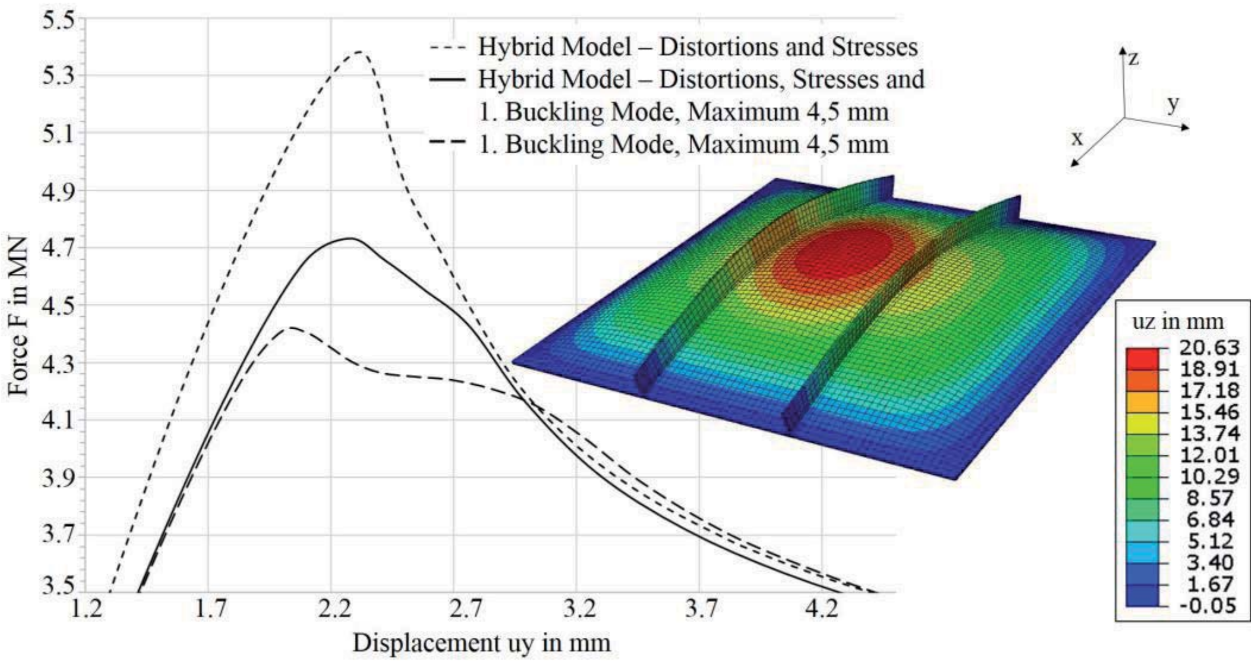

Figure 10: Load deformation curves associated with different imperfect initial geometries and deformation state at ultimate load in the case of "Distortions and Stresses"

6 CONCLUSION

Numerous applications of the analytical numerical hybrid model for the calculation of weld imperfections indicate the significance of the results. The previous comparison with experimental data has already shown very good agreement. The field of application covers different steel grades, several types of joints and the established welding techniques. In the case of consideration, the calculated weld imperfections correlate well with known empirical values. The use of calculated realistic weld imperfections instead of adequate imperfections in the load capacity calculation of the double stiffened structure r in an increasing of the ultimate load in the range of 7 % till 21 %. However, a general statement on the effects of weld imperfections in load capacity calculations cannot be given. The results depend on the geometry, the steel grade, the quantity and positions of the weld as well as the weld parameters. A realistic consideration of these parameters is only possible by an accurate approach of the type that has been presented in this article. However, the approach in combination with loading calculations has to be validated by means of more experimentally determined load displacement curves. These works are ongoing at the moment.

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