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A Novel Method for Welding Residual Deformations Prediction

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Abstract

Prediction of welding deformations for large structure is limited by computational reasons. Nowadays, experience plays an important role in minimizing distortions and the cost of straightening is considered as intrinsic in the process. A fast but reliable simplified method could increase productivity. On one of the factors significantly influence the welding residual distortions is the welding sequence at the global assembly scale and the presence of clamps.
A non linear extension of the Virtual Weld Bead Method which is based on the concepts of the Inherent Strain Method and Strain and Direct Boundary has been developed. Auxiliary elements have been introduced to apply an equivalent load on non linear elements introducing transversal shrinkage as well as angular shrinkage in this first version. A dedicated inverse analysis procedure has been developed to calibrate the equivalent load to be applied and an experimental validation has been performed. The first part of this validation is present focusing on a single welded joint with different clamping conditions, the effect of clamps has been correctly predicted.

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1. Introduction

A common expedient to minimize welding distortions is the use of clamps. Clamps are an economical way to limit distortions but introduce residual stresses which could affect the structural integrity introducing flaws. The use

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of clamps is dictated by experience, the scope of this work is to develop a method which could predict numerically the minimum number of necessary clamps.

Another factor that significantly influences the welding induced residual stresses and distortions is the sequence of the weld runs as well as welds at the global assembly scale. Several authors support this evidence. However, optimizing the welding sequence is difficult and is usually demanded to empirical rules dictated by operator's experience.

The influence of the degree of restraints, simulating different clamping conditions, has been proved experimentally by Rickers (2009) for a T-joint in which different series of springs have been applied on the web. He found that also the tack welds could have an influence on the degree of restraint.

Kang, Seo, and Chung (2018) focused not only on weld sequence optimization but also on generating feasible welding sequence automatically. Besides the feasibility of the welding for accessibility reasons, productivity constraints such as minimizing turn over to facilitate flat position welding, time needed to change the welding process and minimizing movements of part during manufacturing must be taken into account. De Fazio and Whitney (1987) presented a method to generate valid assembly sequence for mechanical assemblies, if *n* is the number of relations between parts, *2n* questions are needed to be answered. Qu, Jiang, and Tao (2013) proposed an integrated method for block assembly sequence in shipbuilding utilizing a genetic algorithm to evaluate the best alternatives.

Even the sequence in which the clamps are applied can affect the final position and orientation of the part as noted by Raghu and Melkote (2004). This is a problem more evident in other process technologies but it is one of the many variables that could affect welding deformations. It is known that the gap between plates at the beginning of welding process affects the magnitude of final distortion.

In the present paper the simplified method, an evolution of Romanin et al. (2020), is presented and the first part of the experimental validation. The experimental validation is focused on a single welded joint with different clamping conditions.

2. Auxiliary Weld Bead Elements

Simplified methods using shell elements take advantage of linear elastic material models for the fast solution time offered. The disadvantage of using linear elastic models is that the order in which the load is applied is indifferent. Some authors have introduced interface elements in the welded joints to take into account the influence of the change of gaps during welding. However, even with non linear interface elements the spring back effect at clamps removal could not be taken into account.

It is clear that in order to take into account welding sequence some sort of non linearity has to be introduced. The novel method should also be implementable in a general purpose FE code.

Clamping and fixtures are normally employed during welding to minimize distortion at the cost of increased residual stresses. When fixtures are removed there is an elastic spring back and the welded joint recovers part of the deformation. This phenomenon could not be modelled when using a linear elastic material model. In fact, if the restraints in the FEM model are disabled, corresponding to removing the fixture in the assembly process, the deformed shape will be always the same, irrespective of the welding sequence. The linear elastic procedure could be considered acceptable if the amount of spring back is limited, thus the deformed shape of the clamped workpiece corresponds to the released workpiece. Another solution is to calibrate the equivalent load basing on welding joints with restrain but a priori knowledge of the results is needed. It is also more inconvenient to maintain a database.

The idea is to extend the virtual weld bead method introducing elastic plastic elements in the virtual weld bead region in order for the model to be path dependant on load application.

Being able to apply the superposition principle is essential to make this simplified method working by decupling each deformation mode. Because with non linear material the loads cannot be superimposed to obtain the desired deformations, an efficient solution is to apply each load type, angular and shrinkage, on different regions. The relationship between the load and each deformation mode is non-linear but each deformation mode could be superimposed as in Fig. 1.

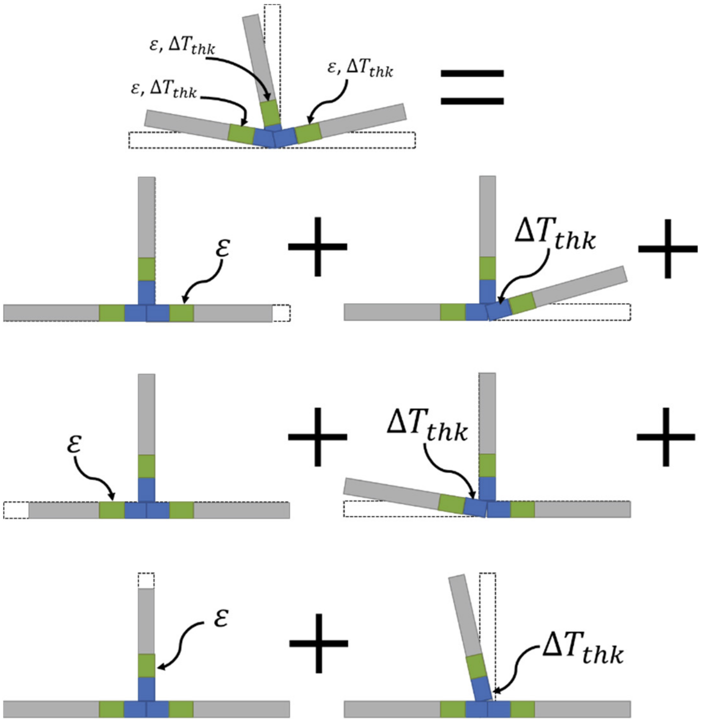

Fig. 1. The superposition is assured by applying each deformation mode load on different regions. In the blue region the angular deformation is imposed while in the green region the transversal shrinkage is imposed. Superposition is assured by dividing the non-linear load types in different regions.

For this reason, the weld bead region is simplified as in Fig. 2, the virtual weld bead is divided in two equal regions. Every side, which has a global fixed width L/2=10mm to speed up the geometry preparation phase and be independent of the joint geometry, has been split into two regions to assure an equivalent load calibration.

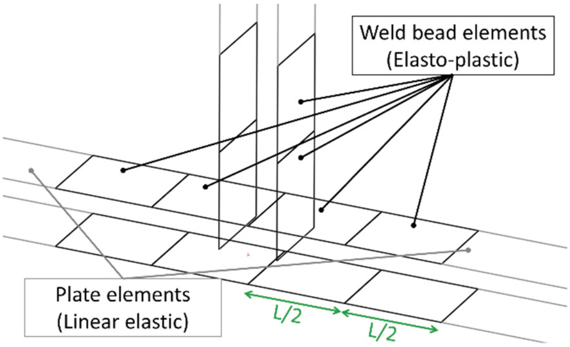

Fig. 2. Virtual Weld Bead regions utilized in the non-linear version

Another important feature is that the equivalent load, representing weld shrinkage, is applied through the use of auxiliary elements and not directly to the non linear virtual weld bead region (Fig. 3). Auxiliary elements are created in correspondence of non linear weld bead elements and are divided into two regions defined before.

Using auxiliary elements to apply the load proved necessary to have the desired flexibility on the curvature and, most importantly, introduces one more variable that could be used to calibrate the effect of restraints as it will explained later on.

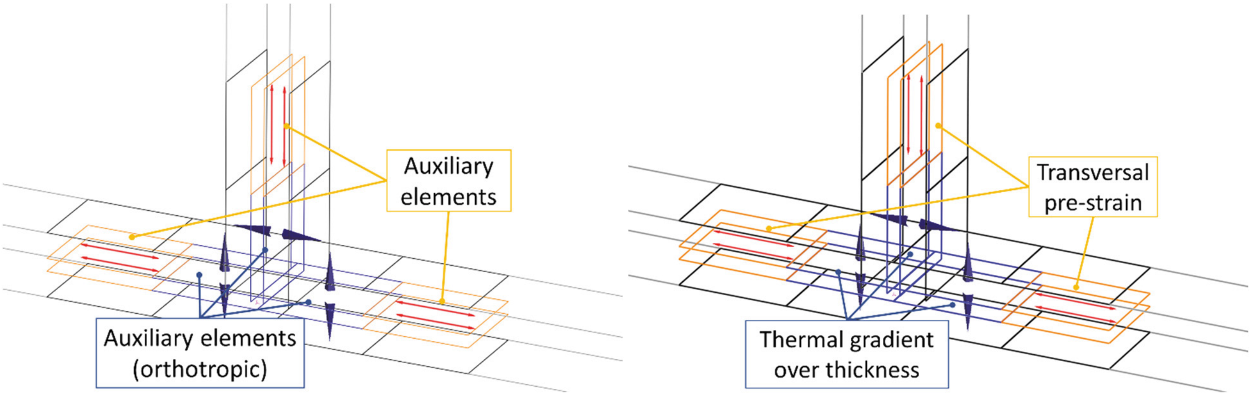

Fig. 3. Auxiliary elements division and type of load applied. The auxiliary elements are superimposed to the virtual weld bead

Angular deformation is applied only on the internal virtual weld bead region trough the use of auxiliary elements. Internal auxiliary elements are orthotropic shells in which, while the mechanical properties are isotropic, the thermal expansion coefficient has been defined in one direction only. For simplicity the coefficients have been fixed to $\alpha_1 = 0\,[1/°C\,]$ int the longitudinal direction and $\alpha_2 = 1\,10^{-6}\,[1/°C\,]$ in the transversal direction. The transversal shrinkage is applied only on the external virtual weld bead region using an auxiliary element.

The yielding point is defined at the steel nominal yielding point and, to maintain a simple and efficient model the same elastic perfectly plastic material law has been applied to all the weld bead elements of the assembly. In order to avoid convergence problems, a small plateau slope of E/100 has been assigned.

In summary, after the joining plate has been activated, the first step of the proposed simplified method is to activate auxiliary elements. The elements are activated using the morphing options, meaning that they adapt to the deformed shape not introducing any stress in the model. Only in next step the equivalent loads are applied to the auxiliary elements. In the last step, auxiliary elements are removed and a portion of deformation is maintained by the plastic strain introduced in the non linear region.

The inverse analysis procedure has been modified in order to include the two stages of the non linear simplified method:

- Auxiliary elements activation and equivalent load application
- Auxiliary elements removal with subsequent loose of elastic contribute

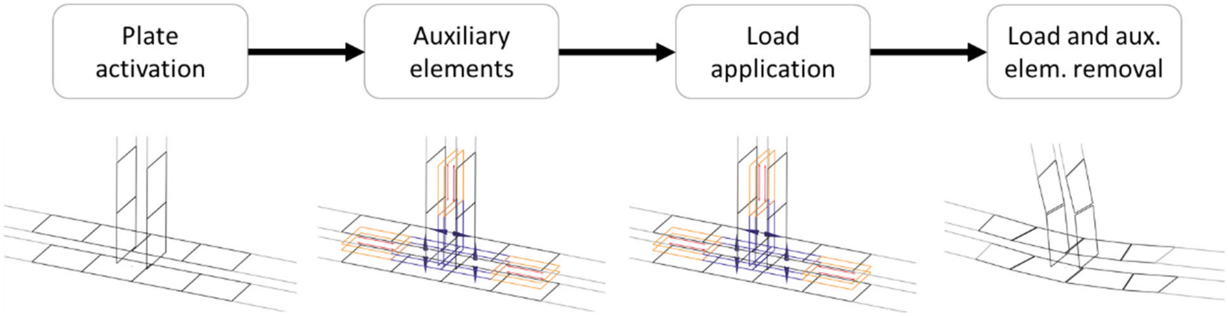

Fig. 4. Steps needed to simulate a welded joint

The only variable that has still to be defined is the thickness of auxiliary elements. The thickness influences not only the load that has to be applied, which is not a problem because is taken care by the inverse analysis, but more importantly the stiffness. In fact, the stiffness of auxiliary elements affects how the joint interacts with other regions of the assembly or with clamps. Using a high stiffness, the deformation field is less affected by the nearby stiffness. Ideally, the thickness should be also calibrated by having another reference case for each joint in which some degree of restraint is present.

2.1. Influence of Auxiliary Element Thickness

The elastic return is schematized in Fig. 5, following the same scheme for a different set of auxiliary elements thicknesses it is obtained the graph of Fig. 6. It can be noted that a thickness 1t has results closer to the free welding case, while a thickness of 1/5t has almost no residual deformation, where t is the thickness of the respective plate.

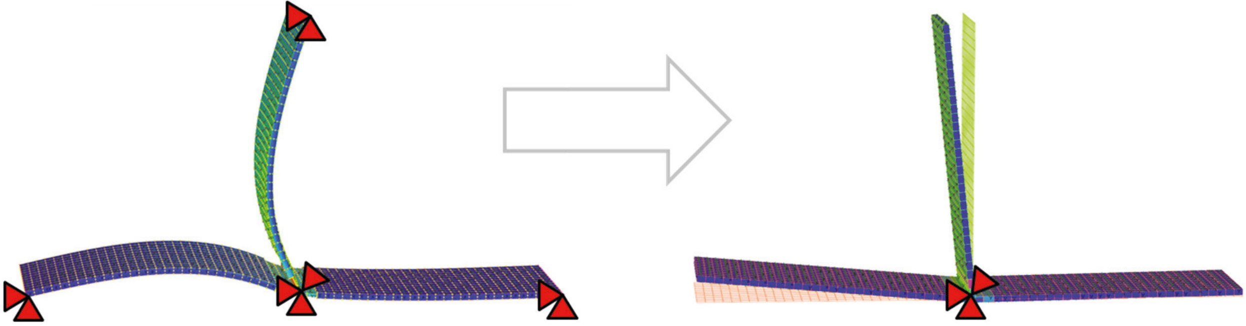

Fig. 5. Scheme of the test for evaluating the response of different auxiliary elements thicknesses

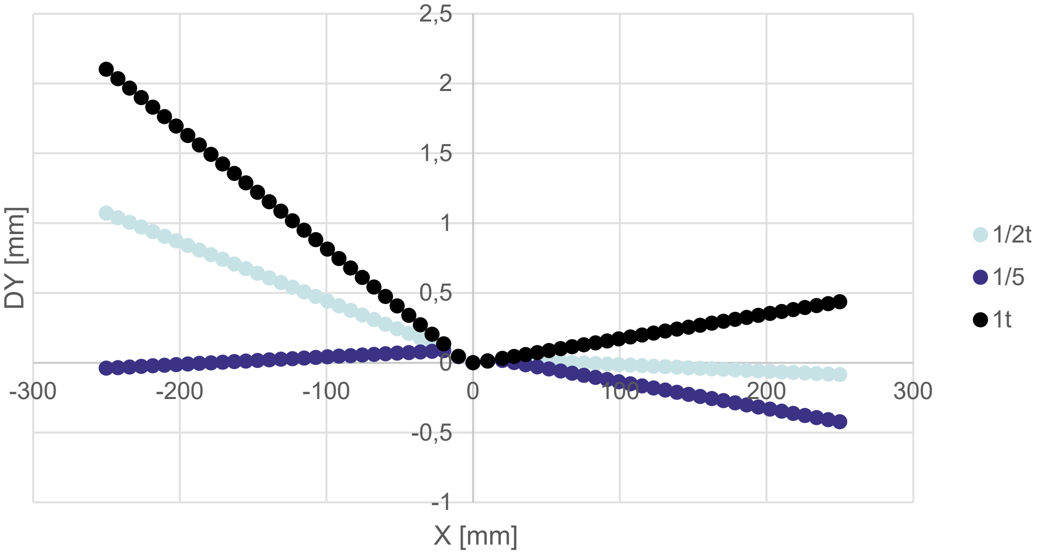

Fig. 6. Different residual deformation after restraint removal for different thickness of auxiliary elements

The case with a thickness of 1/5 t is in agreement with experimental evidence. For simplicity, in this first testing phase, a constant thickness has been assumed for all auxiliary elements.

3. Experimental Validation

Deformations are measured on 3x3 grid of points (Fig. 7) in order to capture quadratic shape deformations. Leica Absolute Tracker has been utilized for measurements. This laser tracker gives results with an accuracy of 0.1 mm. Before measuring the assemblies, they are tack welded to a support because manually positioning the probe could cause the assembly to move. When the stiffener is attached, in order to measure all the points, the laser tracker has to be moved to measure the points that are hidden by some plates. The reference state is taken after tack welding, when the plates are in their nominal position. Measurements after welding have been performed when plate temperatures were lower than 40° C.

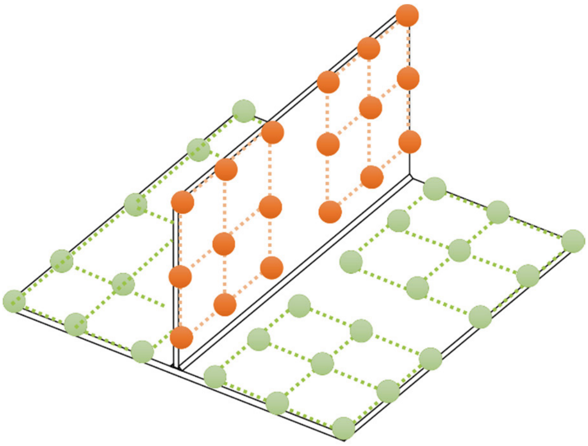

Fig. 7. Grid of points for deformation measurement

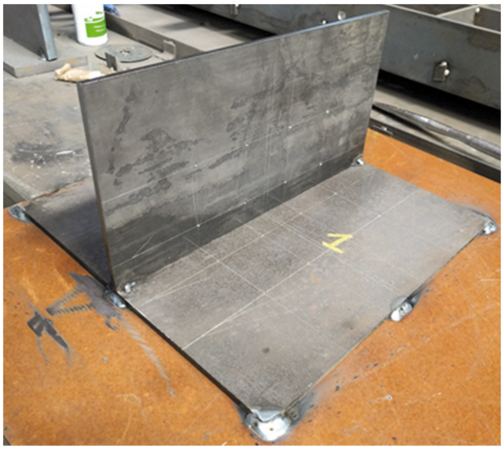

Fig. 8. Tack welded specimen

The welded joint is composed by a flange 8 mm thick, a web of 6 mm and a weld throat 4 mm. It has been welded in the horizontal position. The joint in Fig.8 has been welded without any restraints and with tack welds. The results are then compared to assess if the simplified method is able to take into account the presence of clamps.

3.1. Free Welded Case

Two tests have been performed without any tack welds to fix the flange. It could be noted that out of plane deformations are the same on every section for the flange (Fig. 9) while for the web there is some “torsion” due to the direction of welding (Fig. 10). This type of phenomenon would be too detailed to be included in a simplified method, the uncertainties should include this error.

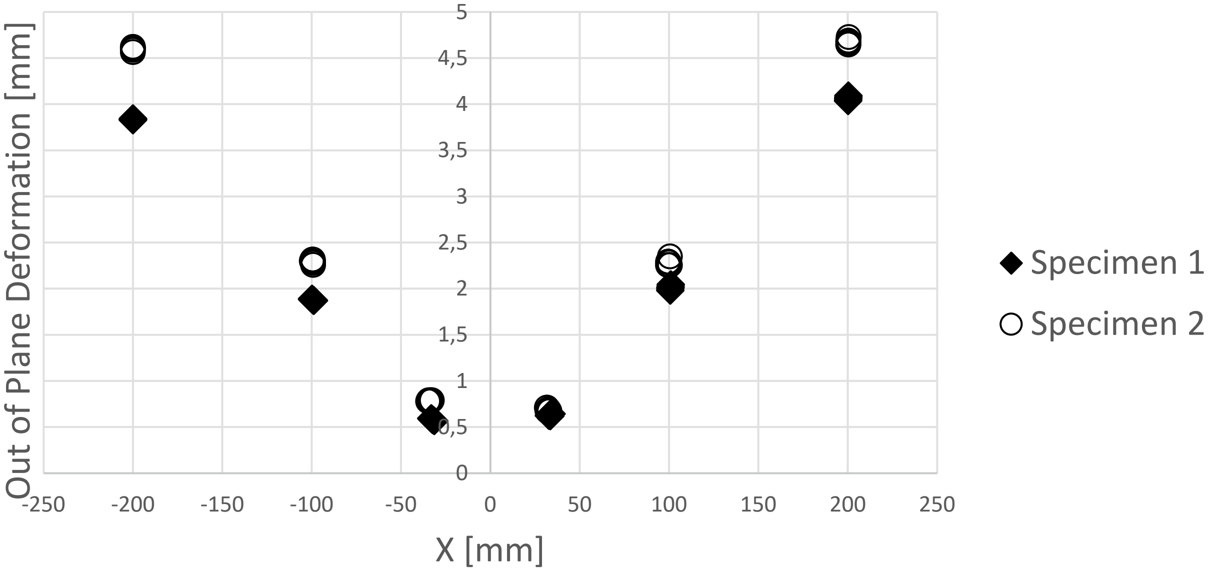

Fig. 9. Comparison of the flange out of plane displacements between 2D numerical cases and the first two specimen

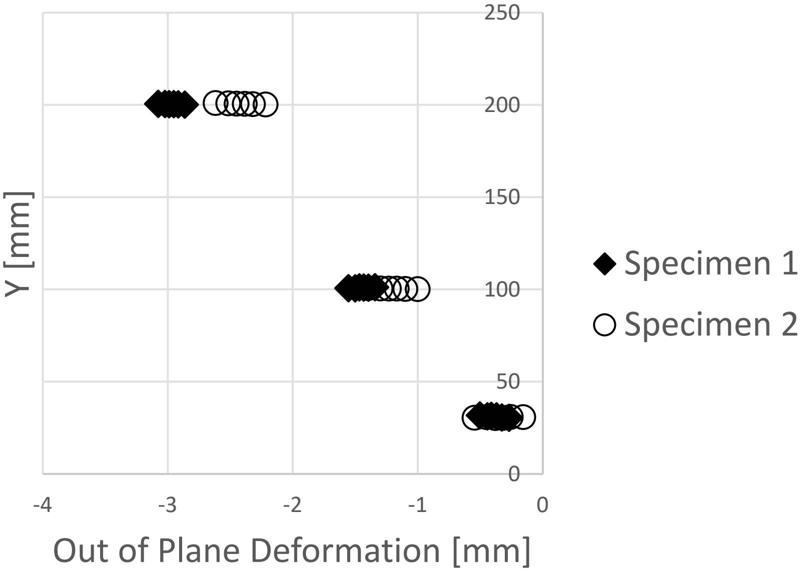

Fig. 10. Comparison of the web out of plane displacements between 2D numerical cases and the first two specimen

The inverse analysis was performed assuming an auxiliary element with a thickness of 1/5t, a bilinear material behaviour with an hardening of E/100.

Table 1. Equivalent loads from inverse analysis.

	Flange Left		Flange Right		Web	
	ϵ	ΔT [°C/mm]	ϵ	ΔT [°C/mm]	ϵ	ΔT [°C/mm]
Test 1	0,011507	-90558,6	0,011507	-90150,8	0,011495	113148,6
Test 2	0,011502	-90550,2	0,011502	-90561,5	0,011495	112360,9

The results of the inverse analysis have been applied on the FE model of the clamped welded joint.

3.2. Tack Welded Case

The assembly was constrained with tack welds at the vertexes of the flange and in the middle of the edge as in Fig. 8. For this reason, the flange should not deform. The simplified method resulted in mean error of 0.47 mm for all the measured points. the results are comparable in terms of global behaviour (Fig. 11).

Only the experimental data set has been reported because the first weld has been calibrated with experimental data in both data set.

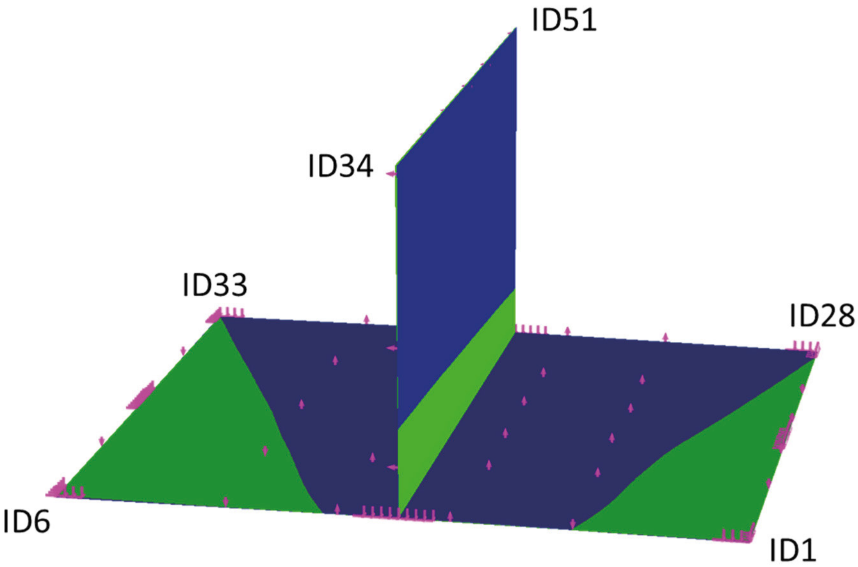

Fig. 11. First Weld only of the Third Test: equivalent load from experimental data of the first weld. The blue is the experimental data while the green surfaces are the numerical results

The numerical results obtained with the proposed simplified numerical method are thus equal for both cases. The numerical results underestimated the deformation of the web as it can be noted in Table 2 for the web vertexes ID 34 and 51. The error is however limited to only 0.57 mm.

Table 2. Detail of the results of vertexes for the CWM data set and the experimental data set. For each axis it is reported the out of plane direction and the coordinate of the numerical point and the experimental point registered

ID	Axis	Raw Data	Absolute FEM	Out of Plane Error (raw)
1	Z	0.00	0.00	0.00
6	Z	0.00	0.00	0.00
28	Z	0.00	0.00	0.00
33	Z	0.00	0.00	0.00
34	Y	203.61	203.16	0.46
51	Y	203.73	203.16	0.57

4. Conclusions

The simplified method consists of applying equivalent loads on Virtual Weld Bead Regions which have non linear material properties. This solution permits to take into account the influence of clamps which is not possible in other available methods in literature if not creating a dedicated welded joints database with different restraint conditions. As matter of fact, tack welding has been taken into account predicting correctly the deformations of the flange. This novel method has thus proven to be more general because for every welded joint only a set of values have to be memorized.

The use of experimental data to calibrate the equivalent load for the Virtual Weld Bead Method with Auxiliary Elements has proven to be precise method but it is unpractical for an industrial implementation where lot of cases are encountered. For an industrial application, Computational Welding Mechanics analysis needs to substitute physical testing to create a joint database.

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