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ON THE INFLUENCE OF FSW IN THE ELASTOPLASTIC BUCKLING LOAD-CARRYING CAPACITY OF EXTRUDED INTEGRALLY STIFFENED PANELS FOR AERONAUTIC APPLICATIONS

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ABSTRACT: Reinforced structures for aircraft fuselages are conventionally composed by base (skin) aluminium plates and reinforcement elements (stringers), joined by riveting operations. During the last decade more effective approaches for reinforced fuselage and wings, such as the Integrally Stiffened Panels (ISP), have appeared. These homogeneous reinforced structures are obtained in an integral form by extrusion, allowing for lower manufacturing costs.

During service conditions, these structures can be subjected to extreme compressive loading conditions and, due to their slenderness and low weight, ISP design must account for a reliable determination of buckling loads. However, complexities of the cross-sectional geometrical shapes, together with the occurrence of elastoplastic non-linear effects prior or after buckling, completely impair the use of analytical tools, being the analysis by the Finite Element Method (FEM) imperative in a reliable design process.

In the present work, the structural performance of ISP structures is assessed, accounting for buckling in the elastoplastic range, by means of numerical simulation with the Finite Element Method. Also, the buckling load-carrying capacity of multiple sets of reinforced structures, composed by a finite number of ISP and joined by friction stir welding (FSW) operations, is also studied. In doing so, it is possible to numerically infer about the influence of the presence of FSW zones in the overall stiffness and mechanical behaviour of ISP structures with complex cross-section geometries.

KEYWORDS: Integrally stiffened panels; Friction stir welding; Elasto-plastic buckling; Finite element method

1 INTRODUCTION

In the present work, buckling deformation modes of an integrally stiffened panel (ISP) is investigated by the Finite Element Method, including elasto-plastic constitutive behaviour prior to, during and after the buckling critical loads. Compressive forces are imposed to this kind of reinforced structure under service conditions, and buckling failure then represents one of the principal design criteria for significant portions of ISP structures when applied to fuselage walls or wing zones in aircrafts. In these situations, it is of extreme importance to design the optimum cross-sectional shapes of the skin and stiffeners along the ISP span in order to sustain the maximum buckling loads in each area, at the same time minimizing the overall wing weight. From a single ISP part to the assembly of fuselage walls, for instance, friction stir welding (FSW) methodology can provide a suitable means to achieve the final structure without no addition of significant weight (when compared to conventional riveting operations) [1].

Recently, it has appeared in the literature some representative works in research in the modelling of buckling of aircraft panels using computational methods, showing that this area is increasingly more active than ever. Not intending to provide an exhaustive state-of-the-art in the field, which would be out of the scope of the present paper, some examples might be nevertheless mentioned.

In reference [2], for instance, it is proposed a computational post-bucking model for fuselage stiffened panels with some guidelines for the nonlinear computational analysis of flat riveted panels subjected to uniform axial compression. Heitmann and Horst [3] also proposed a computationally efficient analysis model for the effective stiffness of stiffened metallic panels in aircraft fuselages. From the joining of single panels standpoint, Murphy et al. [4] have characterized the key process effects of FSW process on stiffened panel buckling performance, showing that welding induced residual stresses can have a significant influence in the panel performance. Mittelstedt have proposed a closed form analysis of the buckling loads of uniaxially loaded

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stiffened composite plates with satisfying accuracy, afterwards extending the formulation to the calculation of minimum stiffener requirements analytically [5,6] for simple cross-section geometries.

Following the previous works in the field and respective milestones, the major goal of the present work is to further investigate the buckling behaviour of upper wing covers coming from integrally stiffened panels (ISP) that are joined by means of friction stir welding techniques. Integrally stiffened panels consisting of two and three modular stiffeners were considered in the present work for the sake of completeness. Accordingly, the effects of boundary conditions and finite element formulation type on the critical buckling load were also evaluated, as well as the influence on the buckling loads of the presence (or not), and respective locations, of the FSW zone [1].

2 PROBLEM DEFINITION

Following reference [1], a fuselage wall composed of 3 modules of T-shaped integrally stiffened panel will be analysed (figure 1).

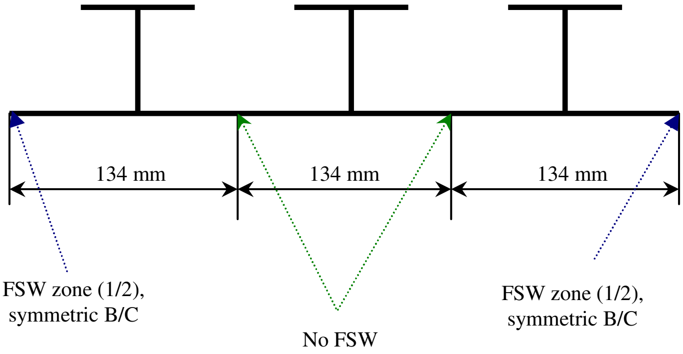

Figure 1: *Sectional geometry (schematic) of 3-stiffner ISP with two-zones FSW*

The modular structure accounts for two zones of friction stir welding (FSW) joining operations, indicated in the figure. Geometry of the individual T-shaped reinforced areas, as well as the non-linear material laws adopted in the numerical simulation, are detailed in reference [1]. Two distinct analyses were carried out using the finite element software Abaqus: a first one considering no-distinctive mechanical properties within the FSW areas and a second one including mechanical properties gradient within the FSW areas.

In both cases, three-dimensional, eight nodes, solid finite element C3D8i were adopted. The choice for this specific finite element came after the validation of numerical solutions against analytical ones, for a simple example of a square plate being subjected to planar compression inducing buckling modes. For this case, both solid elements C3D8 (full numerical integration) and C3D8R (reduced numerical integration) in Abaqus provided wrong results.

Boundary conditions as well as imposed loads in the reinforced walls are represented in figure 2.

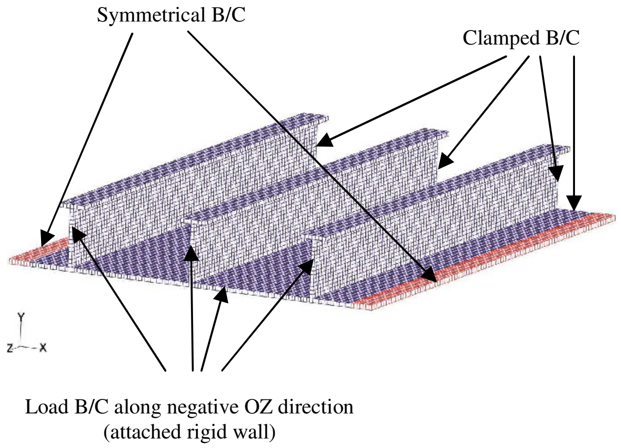

Figure 2: *Boundary and loading conditions in Abaqus for the 3-stiffners T-shaped ISP structure.*

For the compressive loading imposed as represented in this figure, the evolution of the active loading as a function of the longitudinal displacement of the loaded face is according to figure 3, for the two configurations (with no FSW zones and including FSW zones in the model).

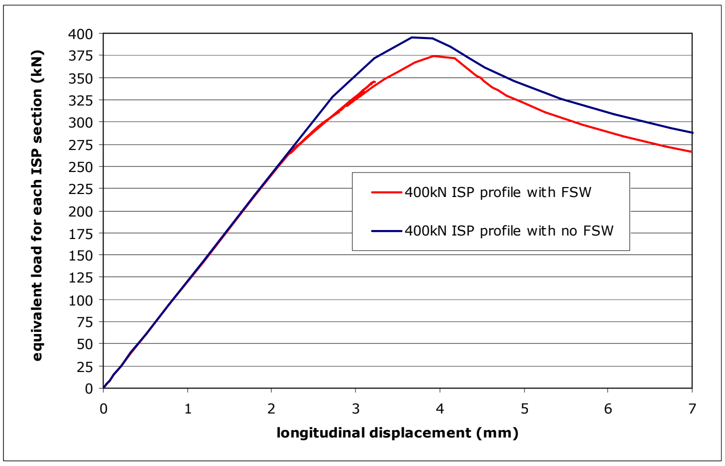

Figure 3: *Equivalent loads vs. longitudinal displacement of the loaded face of the ISP.*

The loading appearing in figure 3 represents the scaled (equivalent) load level, that is, the result coming from the total load applied in the numerical model divided by the number of ISP profiles used (3, in this case). It can be seen from figure 3 that the inclusion of the FSW properties, following the hypothesis and constitutive models from [1], has led to a decrease in the buckling load-carrying capacity of the structural set, as well as a more difficult convergence in the numerical simulation procedure. At this point, it should be mentioned that in both cases, the buckling reproduction with the FE program Abaqus was only possible by the introduction of a geometric imperfection of 1/1000 times the thickness of the representative base plate, and positioned in the mid-length of the structure.

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The deformed configuration of the structure can be seen in figures 4 and 5, along with the contours of equivalent plastic strain levels. The configurations shown correspond to the structural systems including a FSW zone in the lateral areas.

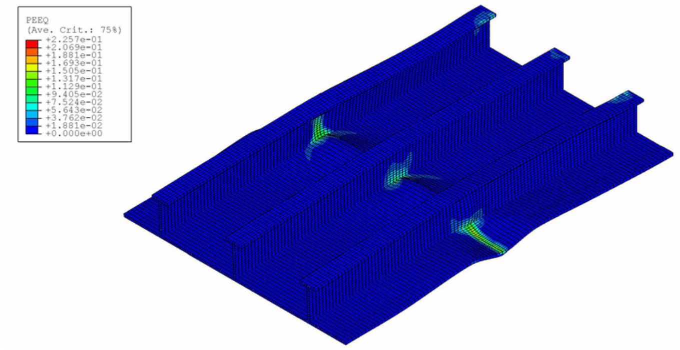

Figure 4: *Equivalent plastic strain level at the limit compressive load (top view, maximum value of 0.23).*

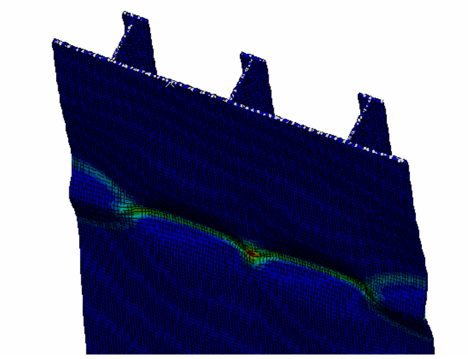

Figure 5: *Detailed bottom view*

Some interesting conclusions can be taken in removing the geometrical imperfection imposed in the three-dimensional mesh system used before and, at the same time change the finite element formulation to a new one based on shell elements (S4, 4 node, fully integrated element in Abaqus).

Despite the expected numerical convergence problems due to the removal of the geometric imperfection that originally triggered buckling, the key idea is to test the performance of shell elements in dealing with localized buckling patterns as those presented in figures 4 and 5. Doing so, it is now considered only two T-shaped Integrally Stiffened Panels, joined together by a single friction stir welding zone, as represented in figure 6.

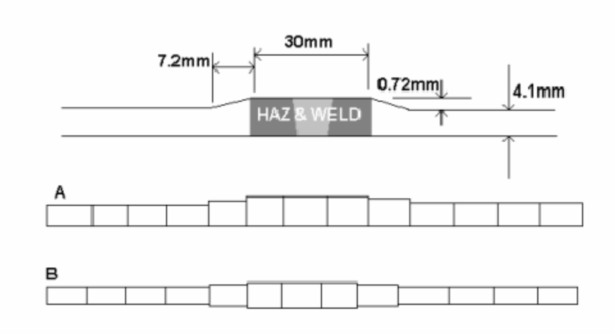

Figure 6: *FSW geometry and numerical models for the joining of two individual ISP structures.*

In the figure, the configuration A is schematically coherent with a three-dimensional finite element model, as the one adopted in the models represented in figures 1-5, following reference [1].

The configuration B in figure 6 is schematically more coherent with a finite element model based on shell elements, and will be the one used in the remaining of this paper.

In order to infer about the behaviour of distinct numerical models, and based on geometry B on figure 6, 4 configurations will be taken into account:

a) Configuration 1: no FSW mechanical properties (homogeneous structures) and a constant thickness values along the base plate (including the FSW area);
b) Configuration 2: 25% dropping of the yield stress values within the FSW zone (compared to the base plate yield stress) and a constant thickness values along the base plate (including the FSW area);
c) Configuration 3: no FSW mechanical properties (homogeneous structures) and a tapered evolution of the thickness close to the FSW area (as in figure 6.b);
d) Configuration 4: 25% dropping of the yield stress values within the FSW zone (compared to the base plate yield stress) and a tapered evolution of the thickness close to the FSW area (as in figure 6.b).

The evolution of the buckling load-carrying capacity of the reinforced structure for each configuration can be seen in figure 7, as a function of the longitudinal displacement (compressive) of the loaded face of the panel.

In the figure, the maximum load level shown is the total load level sustained by the two T-shaped ISP, which is beyond the expected 2x400 KN, where 400 KN is the equivalent maximum load level, as represented in figure 3. The lack of geometric imperfection in the structure may be responsible to this numerical increase in the load level.

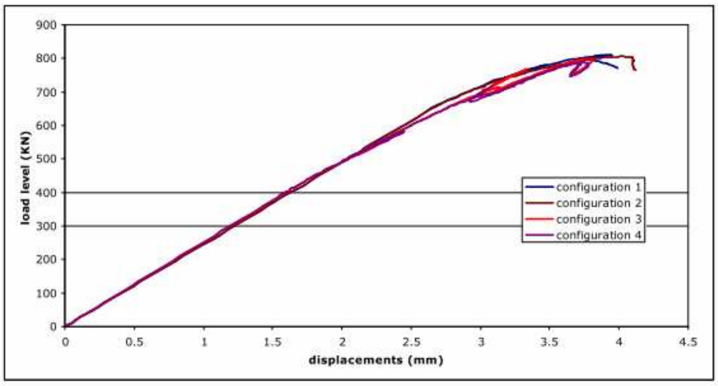

Figure 7: *Total compressive load level for the 2-ISP set under distinct configurations.*

Looking into detail to the results coming from configurations 1 and 2 alone, it is possible to create the evolution represented in figure 8, for the area close to the maximum load levels.

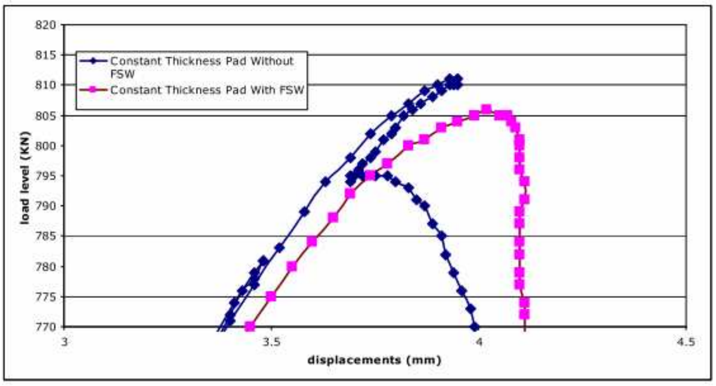

Figure 8: *Total compressive load level for the 2-ISP set for configurations 1 and 2.*

Doing the same for the remaining 2 configurations, it is possible to graphically represent the results as appearing in figure 9, for the area near the buckling point.

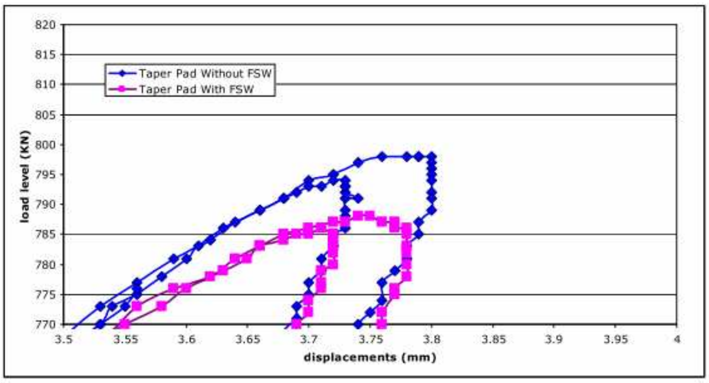

Figure 9: *Total compressive load level for the 2-ISP set for configurations 1 and 2.*

In both graphs (figure 8 and 9) it is visible the amount of dropping in the buckling loads as the FSW mechanical properties are included, as expected.

Nevertheless, it is interesting to note that the critical buckling load for the model with constant thickness values is higher than the corresponding buckling load level coming from the tapered model (variable thickness), which to some extend seems contradictory to the expected. This point will be further investigated in subsequent works.

3 CONCLUSIONS

This work represents a preliminary insight into the numerical analyses of the mechanical behaviour of integrally stiffened panels (ISP), either with homogeneous constitutive properties and also accounting for a simplified model to include the influence of friction stir welding (FSW) zones in the buckling load-carrying capacity under compressive loads.

The ongoing research in this topic, and based on the FEM developed models, is concentrated in the development of mathematical models to the shape optimization of the cross-section of ISP for a given (required) compressive load level and for a number of usual reinforcement types (blades, T-shaped, L-shaped stringers).

Also, it is on course the development of more advanced numerical simulation models for a more detailed and critical evaluation of the residual stress in the heat affected and nugged zones, as coming from the friction stir welding process, and the influence of these residual thermal stress levels in the dropping of the maximum buckling load levels under service conditions.

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