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Effect of Material and Geometric Defects on Buckling Resistance of Stiffened Panels

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Abstract: The impact of material and geometric defects on the buckling failure of stiffened panels is a critical aspect that needs to be carefully analyzed to ensure structural integrity and safety. Stiffened panels are commonly used in various mechanical, aerospace, marine, and civil engineering construction applications. The biggest advantage of the stiffeners is that they increase the panel's bending stiffness with the least amount of additional material. However, any structural system may reach its limit and buckle under extreme circumstances due to a progressive failure of local components. This study focuses on how material and geometric defects affect the critical buckling load, as well as how stiffness and thickness affect it. We've achieved this by using two finite element analyses. The first is a linear analysis that tries to guess the first buckling mode. The second is a nonlinear analysis that uses the results from the first analysis to add localized geometrical flaws using the Riks algorithm in Abaqus CAE. The presence of either material or geometric defects significantly impacts the buckling resistance of the stiffened panel.

Keywords: FEM; buckling; Friction Stir Welding (FSW); stiffened panel; Abaqus CAE; imperfection

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0 Introduction

Stiffened panels are key components in various structural applications, supporting traffic loads and ensuring the safety and efficiency of engineering structures. Buckling is a principal failure mechanism, and engineers are keen to anticipate it analytically to prevent possible failures in structural components. The benefit of reduced-stiffness panels has never been proven adequately, and the poor performance of individual members, accounting material, and geometric variances are assumed to contribute to lowering the structural performance of flexible panels^[1].

Stiffened panels can experience failure in certain loading conditions at the end of their life when damaged. These failings could be attributed to variables, including buckling, yielding, and fracturing, which can cause catastrophic failures and safety risks. Therefore, it is essential to understand the buckling

phenomena related to these profiles to avert structural catastrophic failures. So, it is important to look at the behavior of stiffened panels in a planned way and figure out how these systems buckle when there are flaws in the material or the shape^[2-3].

Buckling is a prominent failure mechanism in engineering design, particularly in maritime and aeronautical structures. These constructions frequently depend on longitudinally stiffened panels for their strength and energy absorption properties. Nevertheless, precisely predicting the maximum strength of these panels is challenging due to the numerous elements intrinsic to the structural model. Buckling is distinct from bending and can result in catastrophic failure, particularly in airframes and maritime structures. We incorporate stiffeners into the panels to enhance the structural response and refine the design by elevating the skin's second moment^[4].

Researchers all over the world are very interested in linear buckling analysis since stability-based

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evaluations were added to European Design Standards by the Advisory Council for Aeronautics (ACA). The objective of European aeronautics research is to attain an 80% decrease in aircraft emissions^[5]. To enhance these structures for weight reduction and fuel efficiency, it is essential to account for dynamic buckling. The impact of weight reduction may be essential for particular load patterns that require thorough analysis^[6].

This research contributes to an ongoing study aimed at creating a logical foundation for determining the maximum strength of reinforced panel structures. Our study has tested a lot of reinforced panels under different types of stress, such as pure shear and mixed uniaxial compression and shear. These tests employed a rigid loading frame with boundary conditions analogous to those present in conventional fuselage and wing box designs^[7]. Based on an analysis on how they respond and fail, mathematical models have been made to predict the ultimate strength of panels that have been stiffened and panels that have not been stiffened under certain loading conditions. In a previous study, we examined the correlation between welding parameters and the impact of these faults on the buckling failure of stiffened panels. This study also examined the influence of welding speed, rotation speed, and the mechanical qualities of the panel on the panel's buckling strength^[8]. The study of how imperfections in the material and shape affect the buckling failure of stiffened panels shows that we are learning more about how complicated structural stability is.

Shahrjerdi's et al.^[9] important study carefully examined different design theories for metal-stitched cylinder-shaped shells. It used finite element models to show that Donnell's theory was wrong because it did not take into account transverse shearing stresses^[10]. Using these measurements from the experiments, a group of shell buckling models were changed to take into account how imperfections have a big effect on the buckling behavior of composite cylindrical shells. The critical buckling pressures of these shells were then calculated^[10-11].

Gomes and Awruch^[12] investigated structural optimizations using sensitivity analyses in the Finite Element Analysis (FEA) environment. This study confirms that initial imperfections and geometric effects significantly influence buckling results. It has two parts: first, performance metrics were set for the

steel plate, frame, and composite interlayer; second, statistical methods were used to define the robustness of the geometry—the performance metric that may improve geometry and other performance metrics needed for the structural context.

The previous work was done using Abaqus software, which uses the finite element method to create models that mimic experimental results for reinforced metal panels. It is important to set up a strong basis for predicting the critical load when buckling happens^[13]. This paper shows that the buckling response is very sensitive to different shapes and the size of initial flaws in the panels. This point is crucial because it stresses the need to think about both material and shape flaws when developing and evaluating aluminum structures. This work also discusses structural improvements using Hybrid Differential Evolution Particle Swarm Optimization (HDEPSO), a metaheuristic algorithm combines Particle Swarm Optimization (PSO) and Differential Evolution (DE). It makes use of PSO's velocity update for exploitation and DE's mutation and crossover for exploration. To prevent premature convergence, the algorithm strikes a balance between local refinement and global search. It is frequently used in science and engineering to solve challenging optimization problems. When compared to standalone DE or PSO, HDEPSO improves convergence speed and solution accuracy, achieving a 14% weight reduction in L-type reinforced panels. This part of the research demonstrates how this work can be practically applied, showing that numerical methods can lead to better designs in aerospace and marine fields.

Huang et al.^[14] studied the ultimate strength of stiffened plates with different loading conditions. Their work showed how shape flaws affect material behavior when reaching maximum stress and built a link between experimental and numerical results. They focused on aluminum panels with various stiffeners after reaching their maximum load during axial compression and lateral pressure. This is crucial in engineering, as these situations often happen, especially in maritime and aeronautical fields. Moreover, they also analyzed that shape flaws can greatly impact elastic buckling and maximum strength, which is a common issue in manufacturing. Huang et al.^[14] discussed a quantitative analysis of the buckling modes and considered the effect of fixed and floating transverse frames on the buckling behavior of

stiffened plates. This distinction is important since it will result in different failure modes and ultimate strength values. Through extensive numerical simulations, it was found that the design of frames has a noticeable effect on the load-carrying capacity of the panels. For instance, Shi et al.^[15] investigated stiffened panels under impact loading and found that initial imperfections and mode coupling greatly affect dynamic buckling strength. They concluded that design guidelines (such as ship classification rules for hull panels) should be updated, their results provide a basis for dynamic buckling strength evaluation and “ship rules modification”.

Zhou et al.^[16] investigated the local and global modes of interaction in stringer-stiffened plates. They validated their analytical model against experimental results, demonstrating the success of numerical methods at predicting buckling responses. This verification highlighted the importance of accurate modeling when predicting structural behavior under load. It gave an analytical solution for elastic buckling of stiffened panels under pure bending and extended upon previous work. Their study carried out a large-scale study of defects and tensile properties, which adds to the understanding of how geometric and material imperfections influence the buckling responses of aluminum members.

Abramian et al.^[17] have been developing non-destructive techniques to predict buckling loads in imperfect shells. Stepwise linear stability analysis is not only needlessly complicated, but their research indicated that it often overpredicts the buckling loads. A nonlinear framework for shell buckling analysis gives us new information about how defects affect the strength of structures and how to better design these parts. They created a nonlinear framework that is different from the usual linear stability analysis that leads to an unrealistically high critical buckling load because imperfections are not taken into account well enough. They argued that the normal approach fails to account for the true loci of buckling, leading to a disconnection between theoretical and actual performance. This summary of conventional approaches is important for focusing on a necessity: better understanding how faults affect structural integrity. They also demonstrated a non-invasive method for estimating buckling stresses without prior fault knowledge, delivering practical solutions to a perennial problem in structural engineering.

If the method proposed by Abramian et al.^[17] works, it will change the way we test metal stiffened panels and make designs that are more reliable by taking into account the natural variations in the material and its shape. In Ref.[18], the probabilistic aspects of how imperfect hemispherical shells buckle were studied. A statistical approach was suggested to model the reduction factors that come with imperfections. Their research showed that defects can interact with each other in important ways. This means that structures that do not work right could be explained using extreme value statistics, which makes designing and judging these structures more difficult.

Falkowicz^[19] conducted an extensive investigation on the stability and failure of thin-walled composite plates with asymmetric geometries. This work gave a clear explanation on how the experiments were done. These experiments include axial compression tests that were improved by acoustic emission techniques to track the progress of damage. This technology is particularly advantageous for enabling real-time damage assessment, hence providing insights into the mechanisms that lead to buckling failure. Putting together acoustic emission data with experimental results helps us learn more about how material and geometric flaws affect the strength of composite plates when they are compressed. This study underscored the need for understanding mechanical couplings and damaged evolution under compressive forces, hence enriching the discussion on material and geometric flaws.

A crucial aspect of the work of Zheng et al.^[20] is the examination of the relationships between defects. The researchers intentionally modified the distance between two defects and found that their interaction markedly affects the knockdown factor. When flaws are adequately distanced, the more significant defect often governs the buckling response. As defects become more closely situated, their interactions become more significant and impose a more complex impact on the overall performance of the structure.

This understanding is crucial for engineers and designers who must consider many defects in practical situations. Moreover, their study of reduction factors is very interesting because it shows that the Probability Density Function (PDF) of these factors is very similar to a Weibull distribution. This article talks about how important extreme-value statistics are in shell buckling and how probabilistic frameworks can

be used to get a better look at how these structures work when they have flaws. When the average defect size and its variability go up, the peak of the reduction factor probability density function goes down, which helps us understand how material and geometric defects affect buckling failure a lot.

Together, these works give a thorough examination on the factors that cause buckling failure in metal stiffened panels, highlighting how important material properties and geometric shapes are to the structure's strength. Our work is the first step in a much bigger project that will look into the results of a lot of different tests that find concentrated material and geometric flaws in the web panel. This study will also look into how these flaws affect the maximum load, the initial buckling mode, and the load displacement history of stiffened panels. This study seeks to investigate the impact of material and geometric flaws on the buckling failure of metal-reinforced panels.

In summary, while previous studies have demonstrated the importance of both material and geometric imperfections on buckling behavior, the intricate interplay between defects induced by Friction Stir Welding (FSW) and inherent geometric inaccuracies remains inadequately quantified. This study addresses this gap by focusing on how do material defects resulting from the FSW process interact with geometric imperfections to influence the critical buckling loads of stiffened panel. Moreover, the relative influence of these parameters, specifically the dimensions of the Heat-Affected Zone (HAZ), the amplitude of the initial geometric imperfection, and the properties of the stiffener material, on the overall stability of the panel.

Through a series of finite element analyses (both linear and nonlinear), this research aims to quantify these interactions and establish a predictive framework for buckling performance. The anticipated outcome is a set of design guidelines that can improve the reliability of stiffened panels in applications where structural integrity is paramount.

1 Materials and Methods

1.1 Mathematical Model of the Nonlinear Static Buckling Analysis

Under a given pattern of applied loading, the equilibrium equations obtained by finite element discretization of the buckling problem take the

following general form of Eq. (1).

$$f(u) = 0 \quad (1)$$

where f is a nonlinear function of the nodal displacement vector u . To solve Eq. (1) for a given load history over a considered time interval, Newton's method is usually used. The idea is to expand the function f around the actual approximation of the solution u^k according to Taylor expansion as:

$$f(u^k) + \frac{\partial f}{\partial u_i}(u^k) \Delta u_i^k + (\Delta u_j^k)^t \frac{\partial^2 f}{\partial u_i \partial u_j}(u^k) \cdot (\Delta u_j^k) + \dots = 0 \quad (2)$$

where Δu^k is assumed to be small. This will be the case when the approximate solution at iteration k is close enough to the exact solution. i and j are spatial coordinate indices (typically representing x , y , or z directions). The third term in the first half of Eq. (2) can then be discarded, yielding the following linear equation:

$$k^k \Delta u^k = -f(u^k) \quad (3)$$

where the term $k^k = \frac{\partial f}{\partial u}(u^k)$ represents the Jacobian matrix. Upon finding Δu_k , the process continues by using $u^{k+1} = u^k + \Delta u^k$ to provide the next approximation until convergence is reached.

1.2 Modelling the Dynamic Buckling of a Stiffened Panel under Distributed Axial Compression

Abaqus CAE, a software renowned for its capacity to perform finite element and extended finite element analyses on structures, modeled the stiffened panel. The modeling process took into account geometric nonlinearities while assuming the material would behave in a linear elastic manner. The shell element S4R from the Abaqus software package was utilized, it features four nodes with six degrees of freedom at each node. It is also capable of addressing material and geometric nonlinearities.

Fig.1 illustrates the geometrical arrangement of the stiffened panel in this analysis. The modeled rigid panel consists of a rectangular plate with three stiffeners in the shape of three equal webs. The base plate's total length is $a = 958$ mm, and its width is $b = 757.5$ mm. The plate is assumed to have a uniform thickness of $t = 0.003$ m.

The stiffeners consist of I-shaped webs with a variable thickness, as detailed in Table 1. In Table 1, t_s is the thickness of the stiffeners, a is the size of the localized defect and E_s is the Young's Modulus of the stiffeners. The stiffened panel consists of both the

plate and stiffener parts. The material properties used in this parametric analysis are based on those of steel, with a mean Young's modulus of $E = 208$ GPa and a Poisson coefficient of $\nu = 0.3$. It is assumed that even though the performance of the stiffened panel may decrease, the material behavior remains linear and elastic.

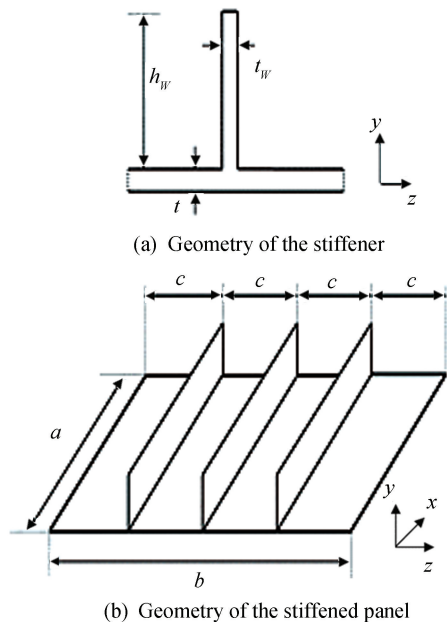


Fig.1 The geometry of the studied stiffened panel with 3 stringers

Table 1 Levels of the parameters studied

Parameter value	t_s (m)	a (m)	E_s (GPa)
Lower	0.002	1/5	E/4
Intermediate	0.003	1/4	E/3
Higher	0.004	1/3	E/2

Fig. 2 illustrates the position of the localized defect in the plate, with a rectangular shape, where l is the length of the defect. The boundary conditions for the lateral edges are as illustrated in Fig.2, which is $U_x = \theta_x = \theta_z = 0$. The edge at $z = 0$ is considered to have fixed boundary conditions, while a uniformly distributed edge load P is exerted on the edge at $z = a$ with rigid wall boundary conditions $U_x = \theta_x = \theta_z = 0$. These boundary conditions fall between the two extreme cases of completely fixed or fully free lateral edges, as depicted in Fig. 3. Therefore, we anticipate the static buckling load to be higher than that of free edges but lower than that of fixed edges.

1.3 Modelling the Material Imperfections for the Panel

Stiffened panels are comprised of two

fundamental elements: the base plate and the stiffeners. These components are joined together through the friction stir welding method, which is recognized for its cost-effectiveness due to superior joint performance, low energy consumption, and minimal emissions. Typical geometric imperfections found in stiffened panels consist of waviness, distortion, and misalignment.

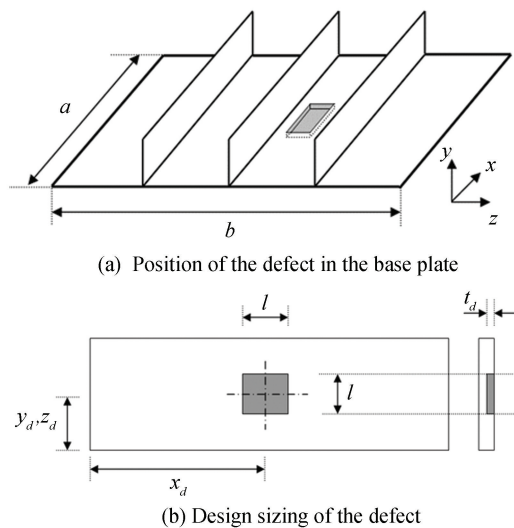


Fig. 2 The location, depth and extension of the dent located on the skin of the stiffened panel

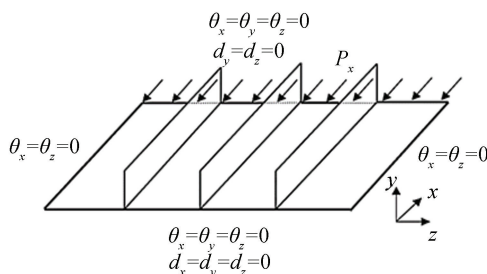


Fig. 3 Boundary conditions of the considered stiffened panel with 3 stringers

FSW is a method of joining solid-state materials that was created at the UK Welding Institute in 1991. Initially, the UK welding institute designed FSW to address issues with fusion welding processes, including cracks, distortion, porosity, and softening, particularly in alloys. Despite its numerous advantages over other welding techniques, FSW does have some limitations on the structure of the welded materials. During the tool's movement, the process creates various microstructural zones, including the Thermomechanical Affected Zone (TMAZ) and the Heat-Affected Zone (HAZ), which result in reduced material properties.

In this study, it is anticipated that the welding process will cause distortion to the skin plate of the stiffened panel. When dealing with geometric flaws in stiffened panels, it is crucial to take into account the impact of these imperfections on the structural integrity and overall buckling failure behaviour. This distortion manifests as a consistent curvature in the transverse direction and is symmetrically distributed about the welding line (see Fig 4). Table 2 shows the different parameters used in this study and their levels, the initial geometric imperfection, the width of the heat affected zone, the Young modulus and the Poisson coefficient in this zone.

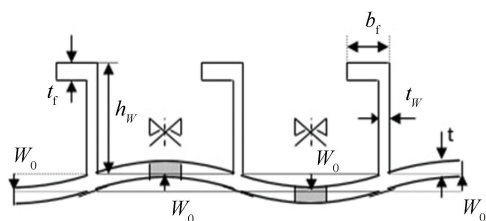


Fig. 4 The initial geometric distortion of the stiffened panel

Table 2 Levels of Young’s modulus and Poisson coefficient in the safe zone and the HAZ

Parameter value	ω_0 (mm)	ω_h (mm)	E (GPa)	ν
Lower	2	25	50.19	0.297
Intermediate	4	50	57.36	0.330
Higher	6	75	64.53	0.363

2 Results and Discussion

Simulations were conducted to evaluate the impact of different factors on the static buckling load. These simulations followed a full factorial design of experiments with $3^3 = 27$ and $3^4 = 81$ combinations, based on the levels outlined in Table 1 and Table 2. Finite element analysis using Abaqus was performed for each combination, incorporating geometric nonlinearities. The number of iterations was regulated by the arc length criterion as per Riks method. This approach enables the determination of the buckling load, which is identified as the limit point on the stress – strain curve resulting from the applied axial load and panel shortening.

2.1 Linear Buckling Analysis of the Stiffened Panel

In this case study, we conducted a Euler buckling simulation to determine the eigenvalues and eigenmodes of the problem. The initial analysis was

focused on predicting the critical buckling load of the perfect panel. Since the structure consists of thin plates and columns, it behaves as a single entity following the Euler buckling expression. Therefore, the critical buckling load is estimated to be the first eigenvalue $P_1 = 1.19321 \cdot 10^6$ N (see Fig.5). Table 3 displays also the first 10 eigenmodes along with their eigenvalues, extracted from the ODB file in Abaqus CAE.

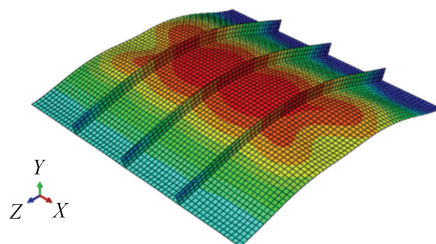


Fig. 5 The first buckling mode with the first eigenvalue $P_1 = 1.19321.106$ N

Table 3 The first 10 eigenvalues

Modes	Eigenvalues (N)
1	1.19321^E+06
2	1.9830^E+06
3	1.24553^E+06
4	1.26154^E+06
5	1.28065^E+06
6	1.34517^E+06
7	1.39018^E+06
8	1.40113^E+06
9	1.52898^E+06
10	1.55975^E+06

2.2 Nonlinear Buckling Analysis of Stiffened Panel Considering Initial Geometric and HAZ Parameters Effect

The analysis in this section took into account the initial geometric imperfection caused by the FSW process, as well as the width and reduced mechanical properties of the HAZ. We created a specific Abaqus model for each combination to calculate the critical buckling load of the panel. After that, an analysis of variance was done on the results. Fig. 6 shows that the critical buckling load changes depending on the amplitude of the initial distributed geometric defect, the HAZ zone, and how these two factors interact with each other. The amplitude of the initial geometric imperfection in Fig. 6 takes the values: $\omega_0 = 2, 4, 6$ mm.

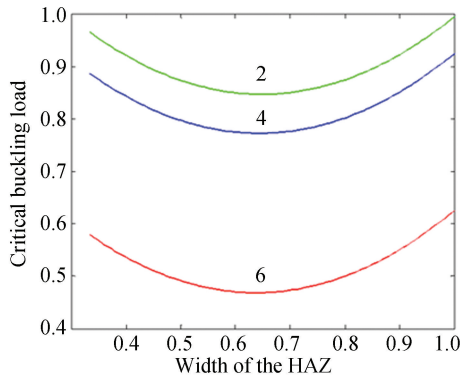


Fig. 6 Variation of the critical buckling load as a function of the reduced width of the HAZ region

By discarding the Poisson’s ratio in the HAZ zone which has only a very slight influence on the results, Table 4 summarizes the results obtained according to the three remaining factors: ω_h , E_h and ω_0 . ω_h , E_h and ω_0 are respectively the width of the heat affected zone, the Young Modulus of the heat affected zone and the size of the initial geometric imperfections which are in the form of distortion resulted from the FSW process.

Table 4 Critical buckling load (P_{cr}) depending on the combination considered

ω_h (mm)	E_h (GPa)	ω_0 (mm)	P_{cr} (N)
25	50.19	2	1197203
25	50.19	4	1030349
25	50.19	6	696690
25	57.36	2	1199391
25	57.36	4	1162461
25	57.36	6	698286
25	64.53	2	1201476
25	64.53	4	1163172
25	64.53	6	700403
50	50.19	4	884426
50	50.19	6	667169
50	57.36	2	1056303
50	57.36	4	780428
50	57.36	6	593837
50	64.53	2	1052572
50	64.53	4	1028870
50	64.53	6	672619
75	50.19	2	1224087
75	50.19	4	1187895
75	50.19	6	729893
75	57.36	2	1222310
75	57.36	4	1187672
75	57.36	6	767896
75	64.53	2	1226288
75	64.53	4	1187728
75	64.53	6	733526

Hence, from the results in Table 4, it is possible to construct a polynomial response surface with a coefficient of determination of $R^2 = 94.5\%$. It is given by:

$$\bar{P}_{cr} = 1.8342 - 1.3434 \bar{w}_h - 1.6943 \bar{E}_h - 0.77015 \bar{w}_0 - 0.24796 \bar{w}_h \bar{E}_h + 0.037504 \bar{w}_h \bar{w}_0 + 0.015449 \bar{E}_h \bar{w}_0 + 1.1967 \bar{w}_h^2 + 1.1077 \bar{E}_h^2 - 1.0321 \bar{w}_0^2$$

Given $\bar{P}_{cr} = P_{cr} / 1226288$, $\bar{w}_h = w_h / 75$, $\bar{E}_h = E_h / 67.53$, and $\bar{w}_0 = w_0 / 6$.

By determining the magnitude $E_h = 57.36 GPa$, Fig. 7 illustrates the progress of the crucial buckling threshold in relation to the diminished width of the HAZ area at various levels of the initial geometric imperfection amplitude. The impact of the HAZ on the critical buckling load is not consistent and shows variations across different widths. It is crucial to avoid welds of intermediate thickness in order to increase the critical buckling stress. For maximum strength, it is recommended to work with either 25mm or 75mm thickness. The use of intermediate values can considerably weaken the strength of the stiffened panel and affect its overall performance. Moreover, minimizing the magnitude of the initial geometric defect is necessary to ensure optimal structural integrity and load-bearing capacity^[8]. Adhering strictly to these guidelines will result in a more resilient and durable structure that can withstand various operational conditions and potential stresses, thus enhancing overall safety and reliability.

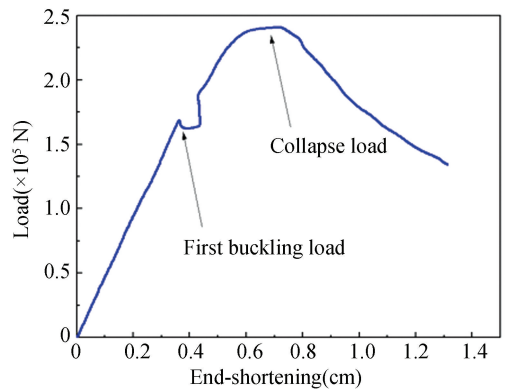


Fig. 7 Collapse load versus end-shortening

2.3 Nonlinear buckling Analysis of stiffened panel considering the localised defect

A full nonlinear analysis was carefully done after a close look at the current flaws and the material’s slow breakdown in the stiffeners and the intact area.

This state-of-the-art analysis utilized the advanced Riks algorithm in Abaqus CAE, ensuring the highest level of accuracy and reliability in the results obtained. The Riks analysis technique utilized in this study is an exceptional and innovative approach specifically designed to observe and analyse the behaviour of the structure after the onset of instability. Additionally, it serves as a valuable tool in accurately predicting the imminent geometrically nonlinear collapse of a structure.

In the conventional approach, an eigenvalue buckling analysis precedes the application of this advanced analysis method. Combining these two essential analyses results in a high level of detailed insights, offering a deep understanding of the collapse mechanism within a structure. Additionally, this integrated approach speeds up the resolution of challenging or snap-through issues that may not show clear signs of instability, ensuring a strong and effective analysis process. The findings reveal the complex details and subtle dynamics of the structure, giving engineers and researchers important information to make informed decisions and take measures to reduce potential risks and improve the overall structural integrity.

In this section, there are a total of 27 combinations resulting from the selection of three levels on parameters: t_s , a , and E_s as per the full factorial design of the experimental table. We established

the mesh size in the FEM (Finite Element Method) simulations at the smallest feasible value for convergence, resulting in 3288 finite elements of the S4R shell type in Abaqus. We determined the collapse load using nonlinear FEM modelling with activated geometric nonlinearities. The step-by-step iterations were controlled using the arc length requirement, as detailed by Riks, and the load as a function of the end-shortening is shown in the curve (see Fig. 8).

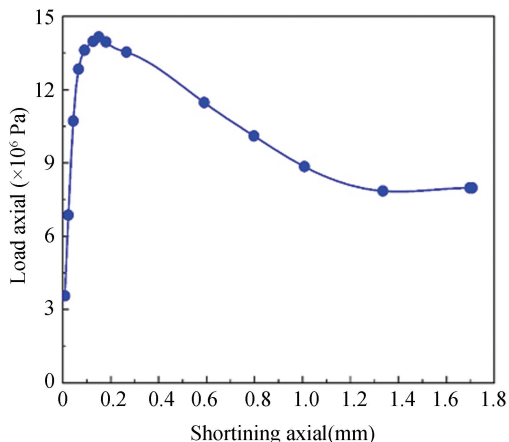


Fig. 8 Applied load versus end-shortening

In addition, an Analysis of Variance (ANOVA) was conducted in the obtained results using an algorithm in order to see the relative weight of each parameter (see Fig. 9). The Analysis of variance test has shown that the presence of localized defect has a huge influence on the obtained results.

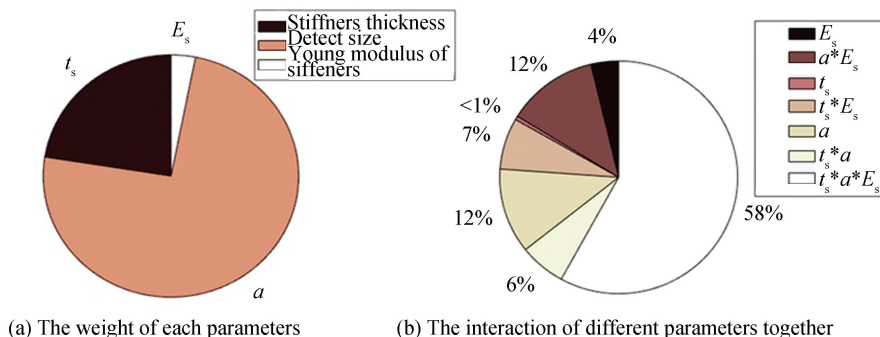


Fig.9 Results of the analysis of variance conducted on the obtained buckling strength loads

To validate the results of this paper, we used the relative important analysis method on experimental results found in previous study^[20]. Relative importance analysis is a statistical method used to ascertain the significance of predictor variables within a regression model. This entails evaluating the prediction efficacy of the complete model against a

succession of reduced models.

The decrease in predicted accuracy with the exclusion of a certain variable from the model helps quantify that variable's relative significance inside the model. It can quantify the contribution of shape features in predictive models, which is a crucial concept in shape analysis, enabling researchers to

identify and prioritize the most significant parametric features in their datasets.

Fig. 10 aligns well with the finding of our analysis, it shows that the initial geometric imperfection has a major effect on the stability of the stiffened panel. μ_{H} and μ which are the Poisson's coefficient in the heat affected zone and the safe zone. Hence, it is recommended to reduce this defect while designing these structures.

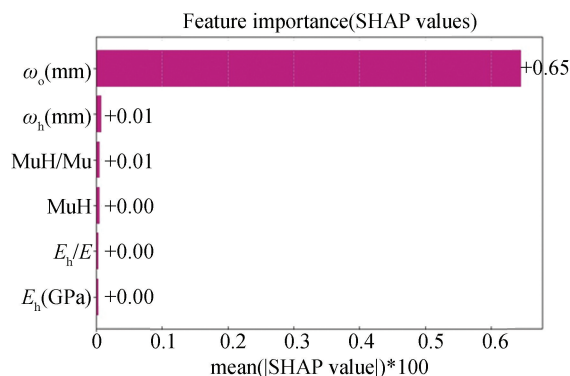


Fig.10 Results of the relative importance analysis method in terms of shape value

3 Conclusion

In conclusion, our study shows that both material defects—especially those from FSW—and geometric imperfections play a significant role in lowering the critical buckling load of stiffened panels. We found that as the size of initial imperfections and the width of the HAZ increase, the buckling resistance of the panels drops noticeably. On the brighter side, by carefully adjusting the stiffener properties and refining the welding process, it's possible to boost the overall stability of the structure. In practical terms, this means that by standardizing welding procedures to achieve an “ideal” weld zone width, manufacturers can produce panels with improved HAZ characteristics that are more resistant to buckling. Additionally, the clear relationship we established between defect size and buckling load offers designers a useful guideline for evaluating and enhancing panel performance.

Looking forward, there's plenty of room to build on these findings. Future research should aim to validate these models experimentally under dynamic loading conditions to better understand how panels react to sudden or repeated stresses. Exploring how changes in stiffener thickness and different material

properties perform under real-world conditions would also help fine-tune our design guidelines. By studying more complex loading scenarios and dynamic effects, we can develop a more robust and reliable framework for stiffened panel designs, ultimately leading to safer and more efficient structures in aerospace, marine, and other critical applications.

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