Buckling Analysis of Curve Stiffened Fuselage Panel of Very Light Jet Aircraft

Devi Chandra1*, Eka Satria1 and Nukman Yusoff2
1 Department of Mechanical Engineering, Faculty of Engineering, Universitas Andalas, Padang, West Sumatera, Indonesia 25166
2 Manufacturing System Integration, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia

Corresponding e-mail: devichandra@eng.unand.ac.id

Abstract. Buckling characteristic of curve stiffened fuselage panel of very light jet (VLJ) aircraft which use one of rivet or friction stir welding (FSW) joint on its stringer-frame-skin connections has been investigated by employing finite element methods. The linear and non-linear finite element analyses were used to determine the effects of stringer shapes and pitch on the buckling load of the fuselage panel. The buckling modes of all fuselage panels have also been observed. The material, boundary, and geometric non-linearity were applied on the fuselage panel in the analysis. Degradation of material elastic modulus around Heat Affected Zone (HAZ) due to friction stir welding processes has been taken into account. The results show that the buckling load of curve FSW stiffened fuselage panel slightly smaller than that curve rivet stiffened fuselage panel for all stringer shapes and stringer pitch. Besides, the curve stiffened fuselage panel with a smaller stringer pitch has a higher critical buckling load and higher loading capacity. Both curve rivet and curve FSW stiffened fuselage panels with close hat stringer shape have a better loading capacity than with the open hat and the Z-stringer shape.

Keywords: Buckling analysis, curve rivet stiffened fuselage panel, curve FSW stiffened fuselage panel, finite element, very light jet aircraft

1. Introduction

To reduce manufacturing cost and weight of aircraft, the aircraft manufacturers have been introduced and developed the integrally stiffened panel (ISP) as an alternative fuselage structure for the conventional stiffened panel (CSP). The emergence of ISP to potentially replace CSP can be attributed to progress made in welding technology such as Friction Stir Welding (FSW) and Laser Beam Welding (LBW). FSW which was patented by The Welding Institute [1] in 1991 is a technique for material joining and processing in which a rotating tool develops sufficient friction heat as it is moved through the joint interface to soften (without melting) and “stir” the two interfaces together. It is a solid-state welding process that occurs below the solidus temperature of the materials being joined to produce a high strength joint with low residual stress and low distortion. FSW can be used to joining the high-strength aerospace aluminum alloys and other metallic alloys that are hard to be welded by conventional fusion welding [2,3]. It also can be applied to various types of joints like butt, lap, T-butt, and fillet joints. The lap joint of skin to the stringer of the fuselage panel can be made by rotating the pin tool moves over the stringer flange to be welded along its length. While the butt joint that connects one fuselage panel with the other is obtained by moving the rotating pin tool at the adjoining edge of the panel.

The strength and buckling characteristic of stiffened fuselage panels is an important aspect in the designing of fuselage structures. A stiffened fuselage panel may buckle in various modes depending on
its dimensions, part geometries, part connections, and loading conditions. Usually, however, buckling occurs in stiffened panel structures when they are subjected to compressive stress. Buckling means that the deflection of the structure diverges from the linearly predicted approach suddenly or gradually leading to a lower loading capacity of the structure. Normally, buckling analysis is conducted to calculate the loading value at which the structures begin to buckle. It can be done in many ways such as theoretical, numerical, and experimental analyses. Theoretical analysis can only be used on simple structures under simple loading and boundary conditions. Theoretically, the buckling strength of the stiffened fuselage panel can be calculated by using equation (1) where \( v \) is Poisson’s ratio, \( E \) is the elastic modulus of the material, \( t \) is the thickness of the skin, \( b \) is skin width, and \( k \) is compressive buckling load coefficient [4]. There are some simplifying assumptions when applying this equation, that is the distance between stringer rivet lines is skin width, the distance between frame rivet lines is skin length and simply-supported on all four edges of the panel.

\[
\sigma_{\text{skin}} = \frac{\pi^2, k, E}{12 (1 - v^2)} \left( \frac{t}{b} \right)^2
\]

For more complex structures such as curve stiffened fuselage panel, the numerical finite element, and experimental analysis have widely been used as the most effective approach in buckling analysis [5].

Many researchers have been conducted buckling analysis of aircraft components such as center fuselage [6], fuselage skin-frame [7], fuselage composite skin [8], spar panels [9]. Some investigations using the numerical and experimental method have also been done to determine and compare the strength and buckling characteristics of both ISP and CSP fuselage panels. ABAQUS finite element codes have been used to model the 2-stiffener and 3-stiffener types of FSW stiffened panel. It is reported that the presence of the weld on the FSW stiffened panel reduced the maximum buckling load due to the reduction in material strength in the weld zone. It depends on the sectional shape of the stringer [9]. Structural response of curve riveted panel and curve machined ISP panel under uniform axial compression loads have been investigated using PATRAN and MCS_MASC finite element code. The results show that the damage model of the integral panel is the stress of the skin exceeding the yield level, and the damage model of the build-up panel is buckling waves cross the stringers on an oblique angle, which is different from the integral panel [11]. Buckling analysis of FSW and rivet aluminum stiffened panels under axial compression load using NASTRAN finite element codes shows that differences between them can be ignored when considering imperfection-free panel and material heat affected zone level [12]. Analysis of the effects of stiffener shapes on buckling strength using PATRAN and NASTRAN software shows that fuselage stiffened panel with L and Z cross-section of the stiffener is a safe design under bending loads, instead, U shape stiffener [13]. The C-section and Z-section of the frame on curve composite stiffened fuselage panel has effects to buckling modes. The buckling of the C-section frame panel firstly occurs in the middle shape, then local buckling occurs in the middle of the frame, while for the Z-section frame panel only local buckling occurs in the middle of the frame [14]. Besides, an investigation on the effects of the curvature of the stiffened panel to buckling behavior shows that the higher the curvature, the higher the number of half-wave in the circumferential direction [15].

This paper presents numerical simulation results that describe the buckling characteristics of curve riveted and FSW stiffened fuselage panels subjected to uniform compression loads. Two configurations of curve stiffened panels based on its stringer pith with three types of stringer cross-sections \((Z, \text{open hat, and closed hat})\) each are numerically examined by finite element method. The panel geometry represents the fuselage panel structures of a very light jet aircraft (VLJ) that is approved for single-pilot operation, 4 to 8 passengers, and the maximum take-off weight less than 10.000 pounds [16].

2. Stiffened Fuselage Panel

The initial fuselage structure of the VLJ aircraft is shown in Figure 1. For simplification, only one-sixth of the fuselage structure is analyzed, called curve stiffened panel as shown in Figure 2. The schematic curve stiffened fuselage panel being analyzed as depicted in Figure 3 consists of three main parts namely
skin, stringer, and frame. The overall dimensions of the panel are arc length of 840 mm, a width of 600 mm, and a radius of 800 mm. Both rivets stiffened fuselage panel as CSP and FSW stiffened fuselage panel as ISP have same dimensions and part configuration but different in joining method of the skin-stringer that is using rivets for riveted panel and using friction stir welds for FSW panel. The skin is stiffened by three longitudinal stringers and two C-section curve frames. The frames are riveted to the stringer by L-shape curve clips and riveted to the skin directly with a rivet pitch of 20 mm and a rivet diameter of 5 mm. The dimensions of all stringers, frames, and clips are shown in Figure 4. The geometrical data of configurations 1 and configuration 2 of both curve rivet and FSW stiffened panels to be analyzed are listed in Table 1 and Table 2 respectively. The stringer, frame, and clip are made of 2 mm thick aluminum alloy (AA) 7075-T6 and the skin panel is made of aluminum alloy (AA) 2024-T3 with a thickness of 1.6 mm. Typical mechanical properties for these material panels are presented in Table 3.
Figure 3. Overall dimensions of the panel.

Figure 4. Geometry and dimensions of stringer, frame and clip.

Table 1. Geometry data of configuration 1 stiffened fuselage panel

| Panel type | Rivet stiffened panel | FSW stiffened panel |
|------------|-----------------------|---------------------|
| Stringer type | Z Open Hat Closed Hat | Z Open Hat Closed Hat |
| Stringer pitch (mm) | 22 22 22 | 22 22 22 |
| Frame pitch (mm) | 40 40 40 | 40 40 40 |

Table 2. Geometry data of configuration 2 stiffened fuselage panel

| Panel type | Rivet stiffened panel | FSW stiffened panel |
|------------|-----------------------|---------------------|
| Stringer type | Z Open Hat Closed Hat | Z Open Hat Closed Hat |
| Stringer pitch (mm) | 32 32 32 | 32 32 32 |
| Frame pitch (mm) | 40 40 40 | 40 40 40 |

Table 3. Material properties of fuselage panel

| Part name | Material   | Elastic Modulus, E (MPa) | Poisson ratio,ν |
|-----------|------------|--------------------------|-----------------|
| Skin      | AA 2024-T3 | 73000                    | 0.33            |
| Stringer  | AA 7050-T6 | 72000                    | 0.33            |
| C-Frame   | AA 7050-T6 | 72000                    | 0.33            |
| L-Clip    | AA 7050-T6 | 72000                    | 0.33            |
3. Finite Element Model

Finite element model and non-linear structural analysis are generated and performed for skin-stringer-frame curve fuselage panels using ABAQUS version 6.10 software code [17]. All parts of the panels were modeled using shell elements with different properties for the un-welded zone and FSW zone elements. The material properties were modeled by an elastic-plastic constitutive model incorporating a Von Mises yield surface and an isotropic strain-hardening flow rule. The plastic strain data was entered as a Table of points for ABAQUS to use in the constitutive model for each material. For the FSW zone, material imperfections due to the welding process are taken into account by the degradation of the HAZ material elastic modulus on the upper flange of the stringer where the degradation is assumed to be 80% and the width of the HAZ is equal to the upper flange width [8].

An appropriate way for representing rivets in an ABAQUS model is the use of the FASTENER feature. FASTENER provides a kinematic connection between two nodes. These nodes are attached to the surfaces which have to be connected. BEAM section connector elements are used to define deformable fasteners. The element set containing the connector elements is referenced using the ELSET parameter on the FASTENER option. To idealize an FSW joint, many researchers have developed a method to model this joint in a finite element model by including the modeling of the degradation of material properties due to the welding process. This study adopts the rigid link multi-point constraint (MPC) approach to model the skin-stringer FSW lap joint [10-12] and the surface to surface CONTACT elements to model the contact between the un-welded skin and stringer flanges.

Element connectivity of the panel model is defined in the mesh module. The stiffened panel is discretized into a sufficient number of elements to allow for the free development of the buckling modes. The mesh density of the panel was chosen based on the size of the stiffener and rivet pitch. A first-order curved quadrilateral 4-noded finite strain general-purpose shell element (S4R) that allows for changes in the thickness was selected along with the mesh illustrated in Figure 5. Physical constraints of the panel are defined with boundary conditions in the load module. The panels are fixed in all six degrees of freedom on one end and simply supported along the longitudinal edges. On the other end of the panel, the enforced displacement of 4 mm was exerted in the longitudinal direction U3.

The first stage in the simulation is a linear eigenvalue buckling analysis to determine the buckling mode shape and buckling stress. An incremental loading pattern was defined in the BUCKLE step where a subspace eigensolver is used to extract the linear buckling modes. The simulation includes large displacements, material plasticity properties, and contact relations between multiple deformable bodies such as skin-stringer joint, skin-frame joint, stringer-frame joint, and frame-clip joint. The second stage of the simulation is the non-linear buckling analysis to determine the static buckling load or buckling load-carrying capability of the panel. The modified RIKS method is used to obtain a solution since the problem under consideration is unsTable. The essence of this method is that it finds a single equilibrium path in a space defined by the nodal variables and the loading parameters, and simultaneously solves for displacements and loads. Since the load magnitude is an additional unknown variable, ABAQUS uses the “arc length” along the static equilibrium path which is given on the data line of the STATIC option to measure the progress of the solution [17].
4. Results and Discussion

4.1. Linear buckling analysis

Eigenvalue buckling analysis was performed to estimate the critical buckling loads (buckling strength) and mode shapes of both FSW and rivet stiffened fuselage panels. About 30 mode shapes were observed for them. Figures 6 and 7 present the first and 19th buckling mode shapes of the rivet stiffened panel for Configuration 1 panel. It can be seen from Figures 6 and 7 that the earliest modes for closed hat stringer panel were local buckling at the skin between one longitudinal edge with adjacent stringer, and local buckling at all skins between stringer and frame for open hat and Z-stringer panel. The local modes were repeated from the first to 18th mode shapes. At the 19th mode shape, the closed hat stringers have different mode shapes compared to both open hat and Z-stringer panel where its mode shapes have three big waves at the skin between stringer along the longitudinal direction while the closed hat and Z-stringer panels have smaller waves along with longitudinal and lateral directions. These differences were possibly affected by the width of panel skin between stringers where the closed hat panel had smaller skin width.

Tables 4 and 5 compare all critical buckling loads of FSW and riveted stiffened panels for both configurations 1 and configuration 2 panel, where \( R \) in both Tables is the ratio of these two values. It can be observed that the critical buckling loads of these two panels for the same configuration are similar such that the differences of the buckling strength of curve FSW and rivet stiffened panels are negligible. However, the difference is significant when comparing Configuration 1 and Configuration 2 panels where Configuration 1 had the biggest critical buckling load compared to Configuration 2 panel. This is possibly caused by the effective width or stringer pith of the panel. Comparing the buckling eigenvalue analysis results, the closed hat stringer panel has the biggest buckling strength for both configurations while the open hat stringer panel has the smallest buckling strength.
Figure 6. First mode shape of Rivet Stiffened Panel for Configuration 1; (a) open hat stringer, (b) Z-stringer and (c) closed hat stringer.

Figure 7. 19th mode shape of Rivet Stiffened Panel for Configuration 1; (a) open hat stringer, (b) Z-stringer and (c) closed hat stringer.

Table 4. Results of linear buckling analysis for Configuration 1.

| Stringer type     | Buckling strength (MPa) | R    |
|-------------------|-------------------------|------|
|                   | Rivet panel | FSW panel |       |
| Closed Hat stringer | 116         | 111      | 1.045 |
| Open Hat stringer   | 96.7         | 94       | 1.029 |
| Z-stringer          | 108          | 104.7    | 1.032 |
Table 5. Results of linear buckling analysis for Configuration 2.

| Stringer type | Buckling strength (MPa) | R   |
|---------------|------------------------|-----|
|               | Rivet panel | FSW panel |     |
| Closed Hat stringer | 95.8     | 92       | 1.041 |
| Open Hat stringer    | 87       | 84.6     | 1.028 |
| Z-stringer          | 91.7     | 89       | 1.03  |

4.2. Non-Linear Buckling Analysis

The non-linear static buckling analysis that uses the modified RIKS method has produced results for the deformation and stress-strain response of the panel under compressive load. Normally it is reported in the form of a load versus end shortening graph for various failure modes of the panel as shown in Figure 8 for Configuration 1 panel. An examination of these Figures indicates that at the initial stage of loading or pre-buckling stage the applied stresses are uniform across the skin panel. As the compressive load is increased, the applied stresses become gradually non-uniform but remain symmetric about the stiffener. When the peak load level is approached, however, the portion of the skin near the stiffener carries more load. Since the stiffener was failing to retain its effectiveness, as evidenced by the reduction of load-bearing in the post-buckling range, the post-buckling behavior after panel buckling is much more ductile than in the case of tripping failure. Figure 8 also shows that the FSW panel was able to undergo a bigger strain before failure than the riveted panel especially for the closed hat and Z-stringer panels. Further details of finite element post-buckling solutions for all panels are given in Tables 6 and 7. Comparing the results of the analysis, it can be observed that the damage load of the riveted stiffened panel is higher than the FSW panel for both configurations, such that the riveted panel has better loading capabilities than the FSW panels. Comparing the results for stringer types, the damage load of the closed hat stringer panel is bigger than the open hat and Z-stringer panels.

Figure 8. Load versus end shortening of Configuration 1 panel.

Table 6. Results for non-linear buckling analysis of Configuration 1 panel.

| Type of Stringer | Z-Open Hat | Closed Hat |
|------------------|------------|------------|
|                  | RSP | FSW | RSP | FSW | RSP | FSW |
| Damage load (kN) | 315.83 | 298 | 441 | 420 | 520.88 | 498 |
| End shortening (mm) | 3.75 | 3.9 | 4.0 | 3.8 | 4.6 | 5.0 |
Table 7. Results for non-linear buckling analysis of Configuration 2 panel.

| Type of Stringer | Z-Open Hat | Closed Hat |
|------------------|------------|------------|
| Damage load (kN) | 277        | 261        | 429        | 409        | 515        | 471        |
| End shortening (mm) | 3.65 | 3.65 | 4 | 5 | 5 | 4.6 |

Figure 9. Failure shape of RIKS method for Rivet Panel Configuration 1; (a) open hat stringer, (b) Z-stringer and (c) closed hat stringer.

Figure 10. Failure shape of RIKS method for FSW panel Configuration 1; (a) open hat stringer, (b) Z-stringer and (c) closed hat stringer.
Figure 11. Failure shape of RIKS method for Rivet Panel Configuration 2; (a) open hat stringer, (b) Z-stringer and (c) closed hat stringer.

Figure 12. Failure shape of RIKS method for FSW panel Configuration 2; (a) Z-stringer and (b) closed hat stringer.

Figures 9 - 12 above show the failure modes of the curve rivet and FSW stiffened panels for Configuration 1 panels and Configuration 2 panels. For all panels, it was observed that at the initial load stage or small compressive load, the skin was able to absorb this load. However, when the load increased the skin begin to buckle and the load-carrying capacity of the skin became seriously weak. Thus, the load was mostly absorbed by the stringers and the skin near them. As the peak load level was achieved, the stringer stress rose to yield stress, tripping the edge of the stringer, and stringer bending will occur, and thus the panel could not stand the compressive load and the panel underwent total failure. This damage mode is similar to the result reported by [11] where for built-up curve stiffened fuselage panel, the damage modes are buckling waves cross the stringer on the oblique angle.

5. Conclusions

The simulation work above aimed to study the buckling behavior of a curve rivet stiffened panel and curve FSW stiffened panel subjected to an axial load. Three types of stringer cross-sections with two configurations of stringer pitch were numerically tested utilizing a simplified finite element model. The results of the analysis can be concluded as listed below:

- Concerning critical buckling load, no significant differences between FSW and rivet stiffened fuselage panels were found when considering material HAZ elastic modulus degradation level of welding.
The curve rivet stiffened fuselage panel has better loading capability than FSW stiffened fuselage panel. Comparing the stringer pith, configuration 1 fuselage panel (small stringer pith) has a higher critical buckling load and higher loading capacity than Configuration 2 fuselage panel. Comparing the stringer types, the closed hat stringer panel has better loading capacity than the open hat and Z-stringer panels for both configurations 1 and 2 of the fuselage panels.

Acknowledgments
The authors wish to thank the Faculty of Engineering Universitas Andalas for financial support through publication grant No. 054/UN16.09.D/PL/2020.

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