Finite Element Analysis of Cohesive Contact Degradation Effects on Stiffened Panel Buckling

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Abstract----Buckling instability is one of critical failure mode in thin-walled structures, particularly in weight-sensitive applications like aerospace engineering. Stiffened panels are commonly used to improve structural stability while maintaining lightweight designs. However, the interaction between panels and stiffeners introduces complex mechanical behavior, especially at their interfaces, where contact conditions significantly influence performance. This study investigates the effect of stiffener-panel contact stiffness properties on the buckling behavior of stiffened panels using numerical simulations. Five variations of cohesive elastic properties (20%, 40%, 60%, 80%, and 100%) were analyzed to evaluate their impact on critical buckling load and post-buckling behavior. Linear eigenvalue buckling analysis identified the lowest critical buckling load (85,537 N for mode 1), which was used as an initial imperfection in subsequent non-linear analyses. The non-linear buckling analysis, performed using the modified Riks method, revealed that cohesive stiffness variations had minimal effect on the critical buckling load (ranging from 112.4 kN to 113.1 kN) but significantly influenced post-buckling behavior. Notably, the 80% cohesive model exhibited the highest ultimate collapse load (243.9 kN), while the 20% model showed a sharp load drop post-buckling. The results suggest that cohesive elastic stiffness property is essential for load distribution but not a primary determinant of buckling resistance. These findings provide insights into the role of interface stiffness in structural stability, aiding the design of more resilient stiffened panels.

Keywords: buckling, cohesive degradation effect, stiffened panel, Riks method, FEA

I. INTRODUCTION

Buckling instability is a critical failure in thin-walled structures, particularly in fields where weight efficiency is considered like aerospace industry. Stiffened panels are widely used to enhance the structural stability while in the same time maintaining lightweight design. However, the interaction between the panel and stiffeners introduces complex mechanical behavior, particularly at their interfaces where contact conditions significantly influence structural performance. In practical applications, the connection between panel and stiffeners is not perfectly rigid or fully bonded; instead, it involves a certain degree of compliance due to factors such as fastener flexibility, adhesive bonding

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properties; or manufacturing imperfections. These compliances can be characterized as contact stiffness, which affects load transfer mechanism.

Many researchers already performing buckling analysis on stiffened panel with various type of parameter variations. Quinn et al. [1] performed experimental work and simulation of buckling on a stiffened panel under compression loading. The simulation is conducted using ANSYS and the result is close to the experimental work. Chandra et al. [2] performed buckling analysis of curve stiffened fuselage panel of very light jet aircraft using ABAQUS. The author used both linear and non-linear buckling analysis to analyze the buckling behavior. Elumalai et al. [3] performed buckling analysis of stiffened composite curved panel using ANSYS software. While previous studies have extensively investigated the buckling behavior of stiffened panel, most assume perfectly bonded interface between stiffener and the panel. Throughout the time, the fastener flexibility and adhesive bonding are not always perfect. Both fastener flexibility and adhesive bonding can be degraded due to continuous usage.

This study aims to investigate the effect of contact stiffness on the buckling behavior of stiffened panel using numerical simulations. By varying the contact stiffness of the interface between stiffener and panel, the critical buckling load for each configuration is analyzed to determine the sensitivity of structural stability to interface stiffness. The findings will provide insights into the effect of contact stiffness degradation in panel-stiffener interface in buckling performance. The results of this research will contribute to the broader understanding of buckling behavior in stiffened structures and offer an understanding in the sensitivity of contact stiffness elastic properties in buckling performance of a structure.

II. METHODOLOGY

a. Stiffened Panel Model

The specimen used in this research is a thin plate with three stiffeners made from a single machined aluminum plate. The thickness of the thin plate is 2.2 mm with 2.8 mm thick of stiffeners. The stiffened panel model has a total width of 440 mm and total length of 590 mm. The stiffeners have 29 mm height which placed symmetrically within the thin plate. The stiffened panel dimension is based on the experiment done by Quinn et al.[1].

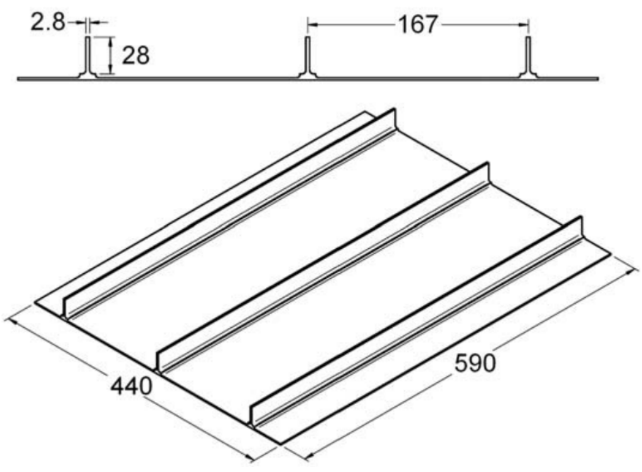

Figure 1. Stiffened panel specimen geometry [1]

Stiffeners and panel are modelled as two different parts. Both stiffeners and panel are made of Al2024-T351. The material properties of Al2024-T351 are shown in Table 1. For the plastic properties of aluminum alloy 2024-T351, the Johnson-Cook plasticity model is used. The plastic properties of aluminum alloy 2024-T351 based on Johnson-Cook model can be seen in Table 2 [4]. The stiffener and panel components are connected using cohesive element which properties are shown in Table 3.

Table 1. Al2024-T351 mechanical properties [4]

Properties	**Value**
Density ($tonne/mm^3$)	2.75E-09
Young's Modulus (MPa)	72000
Poisson's ratio	0.33

Table 2. Johnson-Cook law parameter for Al 2024-T351

Material	**A (MPa)**	**B (MPa)**	**n**	**m**	**T_f (K)**	**T_t (K)**	**C**	**ε_q ($1/s$)**
Aluminum 2024-T351	369	684	0.73	1.7	775	293	0.0083	1

Table 3. Interface properties

Properties	**Value**
Elastic properties	$K_{nn}^* = 12.13\ GPa;\ K_{ss}^* = K_{tt}^* = 3.38\ GPa$
Strength (MPa)	$t_n^* = 45.95; t_s^* = t_t^* = 49.51$
Fracture toughness (N/mm)	$G_{I_c} = 0.98; G_{I_c} = G_{I_c} = 3.71$
Mode interaction - BK	$\eta = 1.40$

b. Finite Element Model

Finite element model and non-linear structural analysis are generated and performed for stiffened panel using ABAQUS software. All parts of the panels were modeled using shell elements. Stiffeners and skin panels are modelled as two different parts. Both components then are attached using cohesive contact. In this study, the adhesive bonding is not modelled as a element, instead it modelled as a contact interaction in ABAQUS. The cohesive properties are assigned in the contact interaction between stiffeners and skin panels. The degradation of cohesive bonding between stiffeners and skin panel is modelled with the percentage of contact elastic stiffness in ABAQUS. There are 5 different variations of cohesive bonding degradation, 20%, 40%, 60%, 80%, and 100% of cohesive elastic properties.

The top side of the stiffened panel is fixed with UX, UY, UZ, RX, RY, and RZ are set to be zero. The bottom side of the stiffened panel is clamped with UX, UY, RX, RY, and RZ are set to be zero. UZ of the bottom side is set free so that it can move in z direction when the load is applied. For the loading condition, compression load in the form of force is applied at the bottom side of the stiffened panel. The illustration of boundary and loading condition of the stiffened panel is shown in Figure 2.

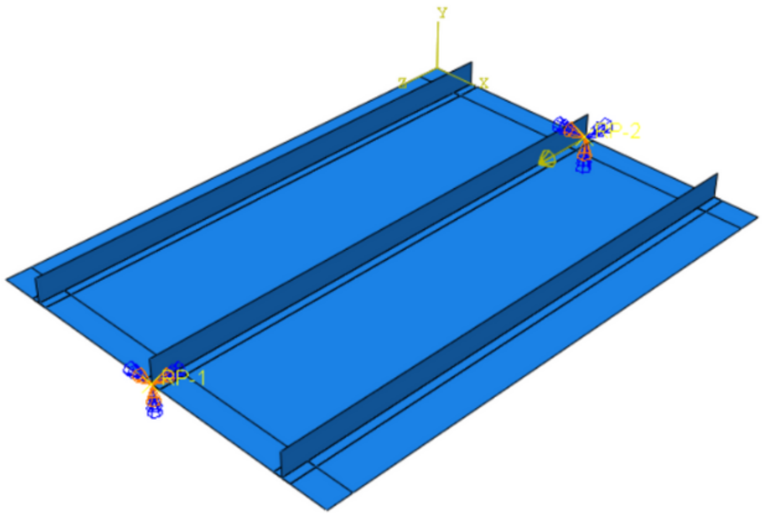

Figure 2. Boundary and loading conditions

The finite element analyses for buckling consist of linear analysis and non-linear analysis, using Riks method. The first stage is linear/eigenvalue buckling analysis. The eigenvalue buckling analysis was done by using ABAQUS, linear perturbation BUCKLE step. The model boundary and loading conditions are set as shown in Figure 2. The applied force is 1 N to normalize the eigenvalue resulted from the analysis. Linear buckling analysis is done to determine buckling mode shape and buckling stress. The result of linear buckling analysis is also used as initial imperfection in the non-linear analysis. The second stage is non-linear buckling analysis, using modified Riks method. The non-linear analysis is done to determine the actual buckling load since it can capture the non-linearity of the structure. The non-linearity of the structure can be originated from non-linear geometry and material. The main idea of modified Risk method is to find a single equilibrium path in a space defined by nodal variables and loading parameter, and simultaneously solves for displacement and loads. In modified Riks method, load magnitude is a unknown variable, thus it introduces additional unknown parameter, load proportionality factor. The load factor at each iteration is modified so that the solution follows some specified path until convergence is achieved. To measure the progress of the solution, ABAQUS uses new parameter called "arc length" along the static equilibrium path in load-displacements space [5].

III. RESULT AND ANALYSIS

a. Linear Buckling Analysis

Linear/eigenvalue buckling analysis is performed to estimate the critical buckling loads and mode shape of the stiffened panel model. The linear buckling analysis is conducted in 100% cohesive stiffened panel model and is set to find 5 first eigenvalue buckling of the model. The result of linear buckling analysis is shown in Figure 3. The eigenvalue resulted in the linear buckling analysis is indicating the load multiplier where the buckling would occur. For this analysis, the applied load for stiffened panel model is 1 N to normalize the eigenvalue, therefore the eigenvalue is directly representing the critical buckling load based on linear buckling analysis. The eigenvalues for each mode are shown in Table 4. While the mode shape is showing how the system deforms in buckling. Generally, the lowest eigenvalue buckling is preferable as it would give the least favorable outcome (lowest capacity). In this case, mode 1 has the lowest eigenvalue, 85537, thus it is used as the initial imperfection input in non-linear buckling analysis.

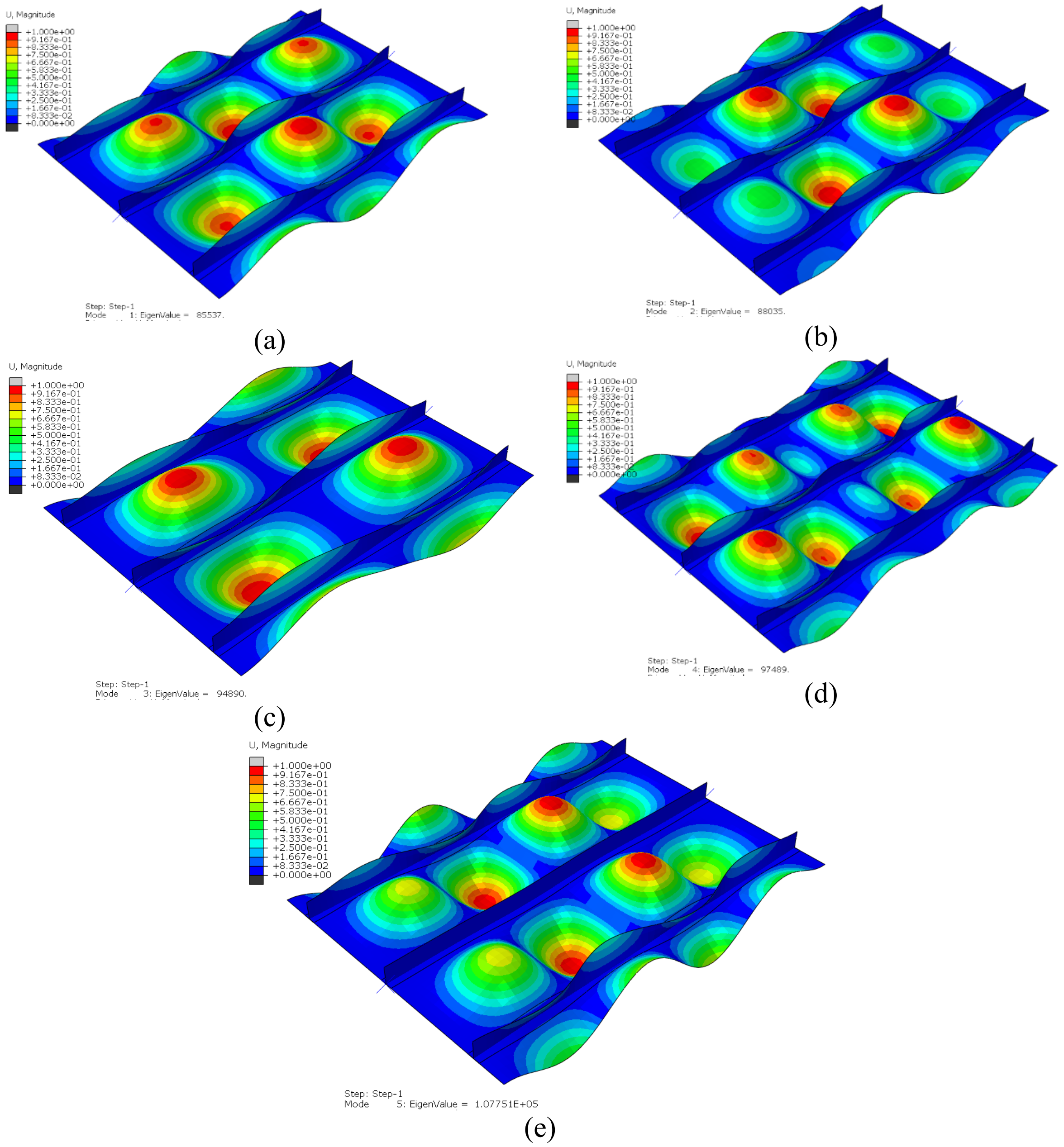

Figure 3. Linear buckling analysis result of 100% cohesive stiffened panel model. (a) mode 1, (b) mode 2, (c) mode 3, (d) mode 4, (e) mode 5

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Table 4. Critical buckling load for each mode

Mode	Critical Buckling Load (N)
Mode 1	85537
Mode 2	88035
Mode 3	94890
Mode 4	94489
Mode 5	1.0075E+05

b. Non-Linear Buckling Analysis

The non-linear buckling analysis that uses the modified Riks method has generated more actual results of buckling phenomenon on the stiffened panel. Five different variations of cohesive elastic properties percentage are simulated using non-linear analysis to find the effect of cohesive elastic properties with buckling performance on the stiffened panel. Figure 4 is showing the effect of cohesive elastic properties percentage to the critical buckling load resulted in non-linear analysis. Although the critical buckling load is tend to increase as the cohesive percentage increases, the different is not really significant. The 20% cohesive variation has 112.4 kN critical buckling load, while 100% cohesive model has 113.1 kN. This critical buckling load different is not really significant compared to the difference in the percentage of the cohesive. Figure 5 is showing the deformation of each variation model in the critical buckling load condition. As it can be seen that the deformation is really similar for all variations because the critical buckling load for all variations is almost the same. For comparison, 0% cohesive is also simulated to see how the behavior of stiffened panel under compressive loading without cohesive at all. The result is showing that the critical buckling load is much smaller compared to others, it is around 46.48 kN. From these results, it can be concluded that the cohesive elastic properties percentage does not give significant impact in the critical buckling load in this stiffened panel model, but it is needed to distribute loading from skin panel to stiffeners or vice versa.

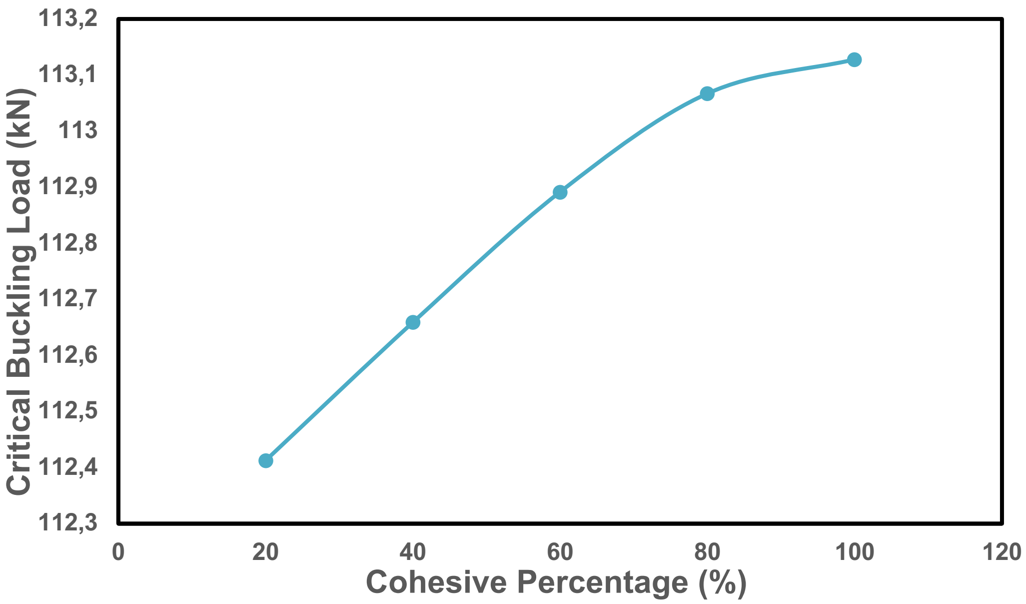

Figure 4. Critical buckling load for each variation of cohesive percentages

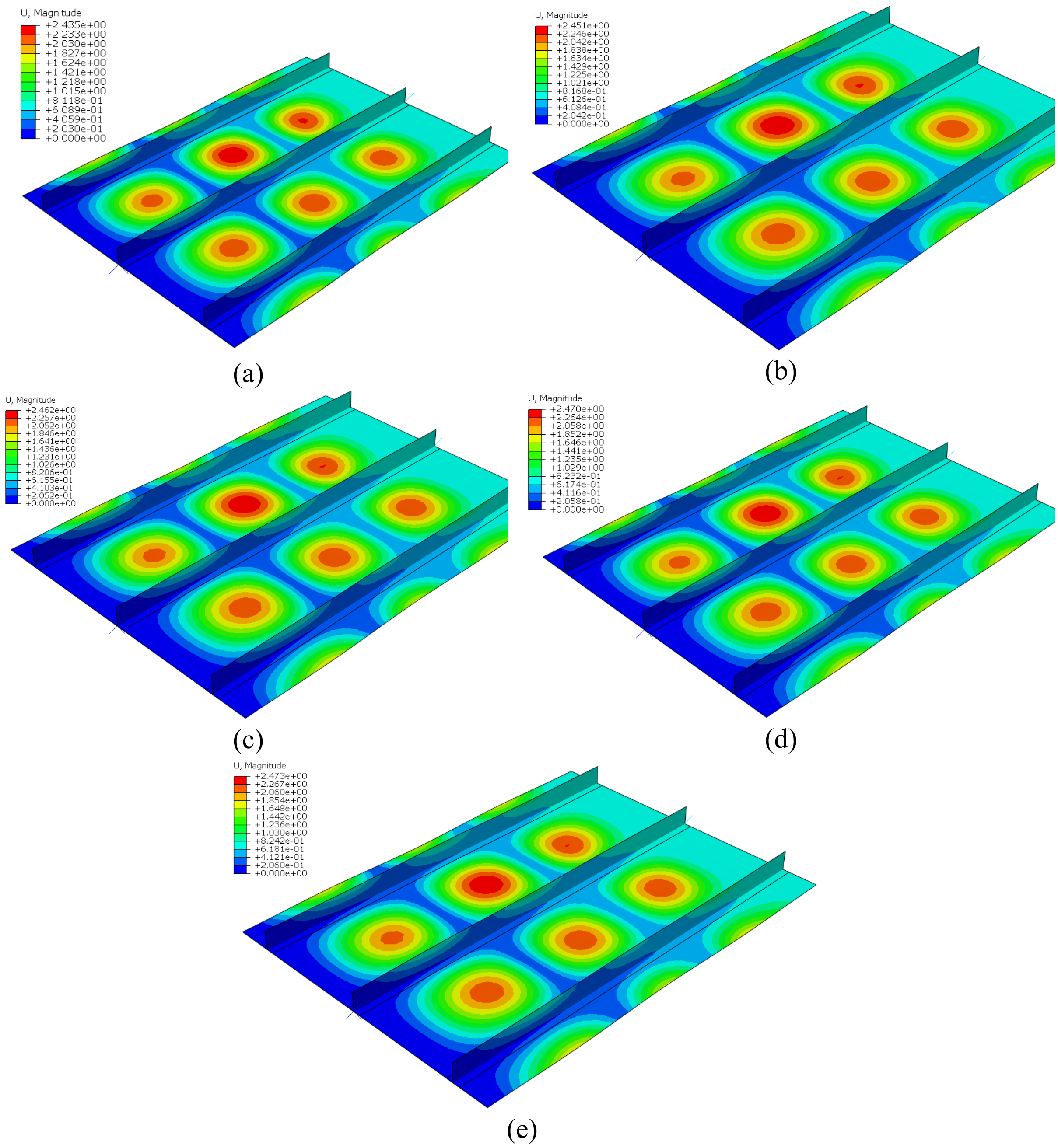

Figure 5. Non-linear buckling analysis for each cohesive variations. (a) 20% cohesive, (b) 40% cohesive, (c) 60% cohesive, (d) 80% cohesive, (e) 100% cohesive

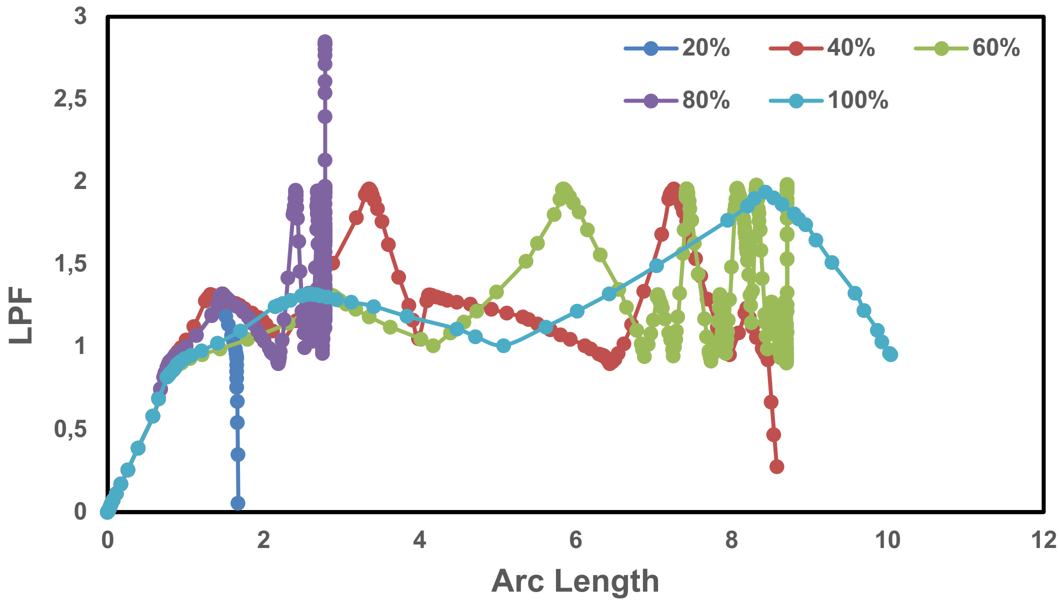

Figure 6. LPF vs Arc length result comparison

Figure 6 above shows the buckling behavior of each model variations when subjected to compressive loading. It can be seen that although all variations have similar critical buckling load, they have different post-buckling behavior. For 20% cohesive model, after reaching the critical buckling load, the loading is dropping significantly, indicating the failure of the model in resisting higher loads. While for other variations, after reaching the critical buckling load, the structure is still able to withstand further loading, indicated by the plot of LPF vs arc length. Figure 6 shows that the 40%, 60%, and 100% cohesive variation has similar post-buckling behavior, as they have similar ultimate panel collapse LPF, around 1.9-2. While for 80% cohesive variation, the stiffened panel can withstand up to 2.85 LPF post-buckling. The ultimate panel collapse load can be seen in Table 5. The simulation shows interesting result because 80% cohesive variation has the highest ultimate collapse load. While 100% cohesive variation has smaller ultimate panel collapse load compared to 40%, 60%, and 80%. From the simulation result, it can be concluded that cohesive elastic properties do not give significant result in the critical buckling load of the model. The cohesive elastic properties are needed so that the stiffener and panel are intact together, but it is not determining the critical buckling load. For the post-buckling behavior, cohesive elastic properties give significant effect. But however, the effect is still random as the author can not find the trend for the cohesive variations. One thing that can be understand form this study is cohesive elastic properties is needed in the interface of stiffener and panel, The value has to be big enough so that it can distribute load from stiffener and panel or vice versa, leading to reach appropriate critical buckling load and continue to post-buckling behavior of the stiffened panel.

Table 5. Ultimate panel collapse load for each variation

Cohesive Variation	Ultimate Panel Collapse Load (kN)
20%	112.413
40%	167.605
60%	169.785
80%	243.898
100%	165.748

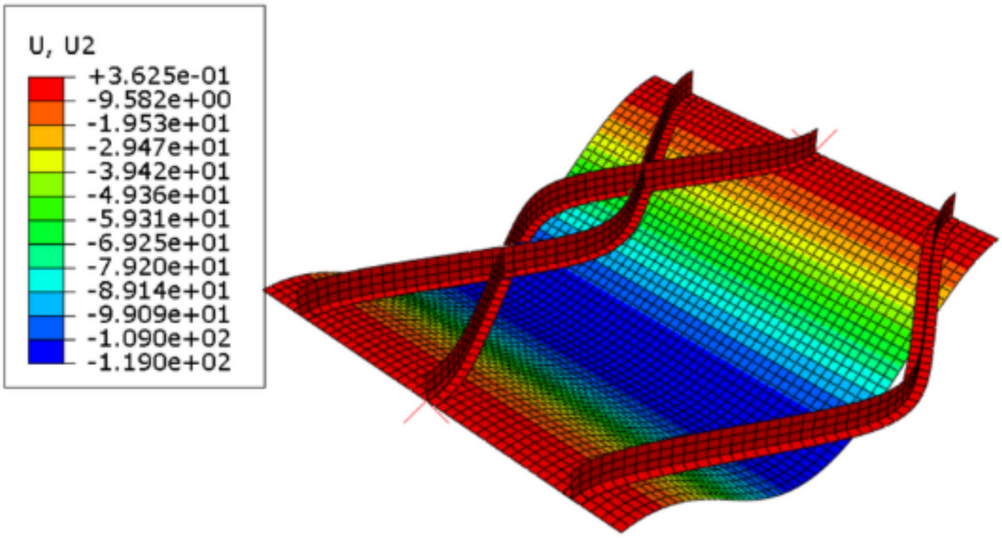

Figure 7. Non-linear simulation result for no cohesive variation

IV. CONCLUSION

The simulations work above aimed to study the effect of cohesive elastic properties in the buckling performance of stiffened panel model. The total of 6 different variation of cohesive elastic properties are numerically tested using a non-linear analysis, modified Riks method. The result of the analysis can be concluded as listed below:

- The cohesive elastic properties do not give significant result in the critical buckling load of the model, but it is needed to keep the stiffeners and skin panel intact and distribute the load to each other.
- The cohesive elastic properties are affecting the post-buckling behavior of the stiffened panel. However, the effects are still unlikely to be understand as the results are still random.
- Cohesive elastic properties are not suitable to be the parameter of cohesive degradation in real application, thus other parameter of cohesive properties are needed to model the cohesive degradation correctly.

Acknowledgement

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