Modeling the Forming Process by Successive Local Deforming for Monolithic Stiffened Panels

Valeriy Sikulskiy
Stanislav Sikulskyi (sikulsks@erau.edu)
Embry-Riddle Aeronautical University https://orcid.org/0000-0002-5199-598X
Kateryna Maiorova
Yuri Dyachenko

Research Article

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Modeling the Forming Process by Successive Local Deforming for Monolithic Stiffened Panels

Valeriy Sikulskiy [1], Stanislav Sikulskyi [2,*], Kateryna Maiorova [1] and Yuri Dyachenko [1]

[1] Department of Aircraft Manufacturing, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine;
[2] Department of Aerospace Engineering, Embry-Riddle Aeronautical University, Daytona Beach, USA, 32114;
* Corresponding author: sikulsks@erau.edu

ORCID	Author Name
0000-0002-5944-4728	Valeriy Sikulskiy
0000-0002-5199-598X	Stanislav Sikulskyi
0000-0003-3949-0791	Kateryna Maiorova
0000-0003-1252-244X	Yuri Dyachenko

Abstract

The study considers a method for forming stiffened monolithic panels by local deformation of the panel ribs. The local deformation is caused by bending moments along the rib towards each other. The goal of the study is to numerically model the forming process of the stiffened monolithic panel utilizing the designed local-impact tool and analyze its effects on the panel, obtaining which experimentally is challenging. The finite element method (FEM) modeling is performed in ANSYS and validated by the experimental forming of a panel made of aluminum alloy analogous to Al 2024. Simulation results provide deformation, stress, and strain distributions along the panel in loaded and unloaded states for various study cases. Furthermore, the effects of finite panel length, width, and forming process parameters such as applied force couples and single versus successive deformation are numerically investigated and discussed. Performed modeling demonstrates the advantages of the forming with the designed tool in terms of low residual stresses and their distribution. Finally, the analysis suggests future modification of the tool, particularly the shape of its grips, to minimize local residual stress concentrations.

Keywords — stiffened monolithic panels, forming, local deforming, panel deflection, plastic deformation, residual stress, numerical modeling.

1. Introduction

Monolithic stiffened panels are widely used in aircraft, spacecraft, and watercraft primary structural frames. Compared to assembled structures, monolithic panels considerably improve geometry, structural and weight performances of a final product. However, the forming process of initially flat stiffened monolithic panels is a challenging task and is one of their major drawbacks. Firstly, aerospace and watercraft vehicles often possess complex surface geometry with variable or double curvature, which is dictated by fluid dynamics, thermal characteristics, etc. For monolithic panels, this requirement means the panels must be formed into these complex shapes (**Fig *1***). Secondly, the process involves coupled deformation of panel skin and ribs that can have variable geometry along the panel. Furthermore, considering the industry's tendency to increase the panel sizes, shape forming becomes an abnormally complicated manufacturing problem. Most of the current industrial manufacturing methods for forming large-scale monolithic panels are limited in terms of efficiency, final panel shape tolerance, and control [1,2].

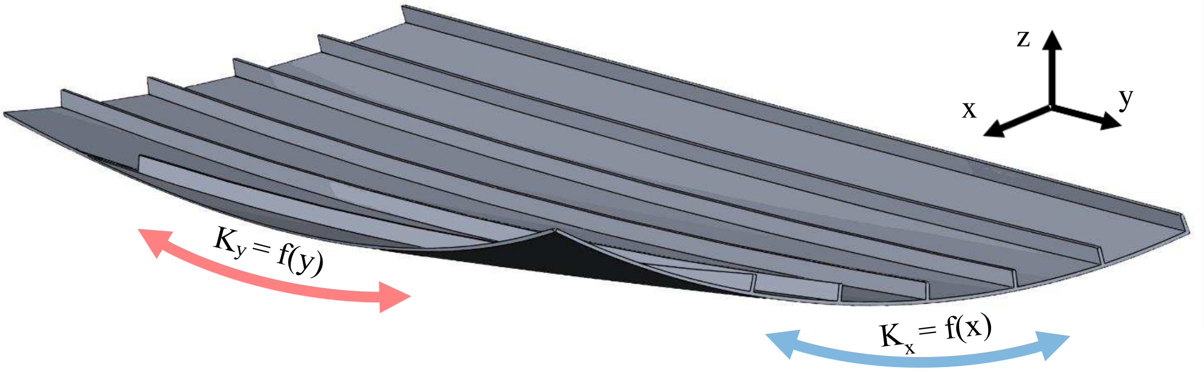

Fig 1 Monolithic stiffened panel with a variable double curvature

New methods are being investigated and developed to assure a high tolerance of the curved panel's external surface. While some recent and attractive efforts include the implementation of additive manufacturing as a component of a hybrid manufacturing of curved monolithic stiffened panels, such methods would still require final panel forming to counter the panel bending due to residual thermal stresses that are created during the additive process and are released during the machining step [3]. Such methods include manufacturing processes that utilize local deformation to produce curved panels, skins, and ribs [1,4,5]. These methods are used not only for forming separate ribs individually but also as major and self-sufficient techniques for forming monolithic stiffened panels into complex shapes. By successively applying local deformation, monolithic stiffened panels can be formed into complex, unsymmetrical shapes. Application of local deformation methods at rough and finish forming stages considerably improves the quality and tolerance of the outer surface of the formed monolithic panel. Besides addressing the issue of rib-skin coupling, local deformation methods are appropriate for the panels with non-uniform structure or discontinuities, e.g., cuts, ribs' edges, varying skin thickness, panel edging, etc. Lastly, manufacturing efficiency and panel shape optimization can be improved by using a compact tooling system that can accommodate geometry control at the measuring stand during the local panel forming [6]. Considering all these benefits of the method, successive local deformation forming is an attractive and promising technology for manufacturing in aerospace and marine industries.

If the tool is designed to apply bending moments to the two parts of a panel rib towards each other, the deformation area and bending angle are decreased considerably (**Fig** *2*a). **Fig** *2*b shows the designed and industrially tested local deformation tool that applies local bending by means of force couples. The tool is fixed on the rib by grips at four contact areas. Then, by hydraulically actuating the tool, two force couples are applied to the areas of the ribs resulting in two local bending moments towards each other. Such a method of generating bending moments effectively realizes the local deformation approach for forming and leads to the following additional benefits due to the particularly small deformation zone, size of the tool, and its weight:

- Precise control of the amount of plastic deformation in the deformed zone. As a result, the springback angle is significantly reduced and can be kept below one degree for low plastic deformations in a panel, considerably less than typical springback angles during conventional forming [7,8].
- In-situ non-contact shape control by means of a measuring stand enabled by the tool's small size [9].
- Portability of the tool for forming large-scale panels due to the tool's small weight and size.
- Versatility of the tool, e.g., its applicability to panels with the various ribs' shapes and height due to the fact that the force couples are applied to the ribs, allows for achieving complex shapes for double-curved panels. This advantage is particularly important compared to other local deformation forming techniques [4,6].

- No need for post-processing the panel. The smooth grips (without notching) with the roughness of Ra 2.5-4 result in a solid grip without slippage between the tool and the rib and do not leave any surface defects on the rib's contact areas that would require additional processing [10].

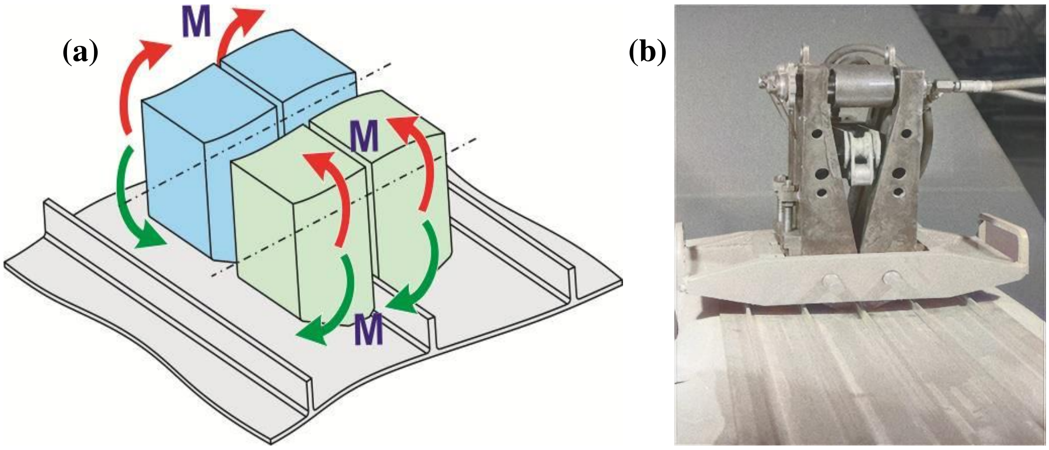

Fig 2 (a) Scheme of rib local deformation by applying bending moments in the direction of red or green arrows to create positive or negative concave shape, respectively; (b) fabricated hydraulically-driven experimental tool fixed on a rib of an aluminum monolithic stiffened panel to shape it by local bending moments through applying force couples

Manufacturing regimes of the forming process for stiffened monolithic panels have not been thoroughly studied yet, and, therefore, are implemented in the industry with caution [11-13]. A thorough study must be carried out to fully benefit from the local deformation method and implement it in industrial manufacturing. One of the major challenges at the initial stages of the forming method development is the modeling of coupled deformation of ribs and skin [14,15]. Current studies do not fully investigate numerous aspects, such as the stiffening effect of the adjacent ribs and skin, skin-to-ribs stiffness ratio, panel length, local state of residual stresses in ribs and skin etc. Meanwhile, these aspects are vital in characterizing the performance and benefits of novel manufacturing processes. Thus, this paper focuses on the major aspects of panel geometry and investigates how they affect the proposed forming process.

Preliminary analysis of the successive local deformation forming process with the proposed tool has already verified advantages of reduced deformation zone and springback angle of less than one degree, as well as the capabilities to achieve various deformation modes, e.g., oblique bending, without losing tolerance and simplicity of the process [10,14]. Thus, the present paper aims to address various technological parameters of the forming process and analyze the effects of the abovementioned aspects on the final panel shape and overall quality. The obtained knowledge would allow to set up and optimize the technological process for the successive local deformation forming with the proposed tool.

2. OBJECTIVES

The paper aims to conduct detailed numerical modeling of the forming process for stiffened monolithic panels by multi-point successive local deformation utilizing the designed tool. The research solves the following tasks to reach the objectives:

- model local bending by the designed tool for stiffened monolithic panels forming;
- determine an appropriate load for the forming processes;
- analyze the local stress state in the deformed area;
- observe the effects of various parameters of the stiffened panel on its deformation;
- evaluate the shape of the panel and stresses in it after the successive local deformation forming.

3. METHODOLOGY

Numerical approach to model the forming of monolithic stiffened panels by successive local deformation was performed in the finite element method (FEM) software ANSYS. The formed panel cross-section is 520 mm in width with a skin thickness of 2.5 mm and five 30x6 mm ribs at a 100 mm step (Fig 3). A panel with a length of 0.8 m, referred to as a short panel in this paper, was used to investigate the major objectives, while a panel with a length of 3 m, referred to as a long panel in this paper, was used to study the effect of length of the forming process. Both panels were assumed to be made of aluminum alloy D16chT (analog to Al 2024), which was modeled as an isotropic material with multilinear hardening using hexahedron (8-nodes) finite elements (SOLID185). The following material properties were used: Young's modulus E = 69.5 GPa, Elastic limit σ_e = 320 MPa, Poisson's ratio of 0.3, according to the properties of 2-10.5 mm thick D16chT panels [16] (similar to Al 2024 properties [17]), and the below stress-strain relation in a small region of post-yield strain used for the multilinear hardening modeling (Fig 4) [18]. The selected range of post-yield strain of the stress-strain curve covers the maximum strains reached in the modeling. While the performed analysis is fixed to the selected representative panel cross-section and material, the major conclusions on the forming method are valid for a wide range of utilized panels.

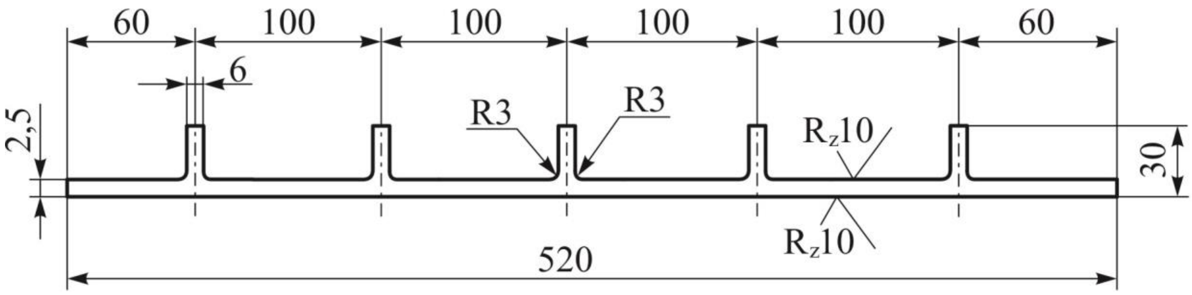

Fig 3 Cross-section of the panels used in the numerical analysis and experiment

The contact effects of the tool were investigated in the previous work and proved the validity of idealizing the contact between tool grips to panel ribs as no-slip contact surfaces [10]. Fig 5 presents the schematics of the local impacts applied to the segment of the monolithic panel's rib by means of local bending moments. In the present study, the bending moments are modeled as force couples applied vertically at the tool's contact areas (25x25 mm) and a rib, as shown in Fig 5. While the experimental tool applies forces perpendicular to the panel, applying forces vertically in the numerical modeling does not yield a considerable error due to the small bending of the panel under the load. Therefore, the magnitudes of the force couples are selected based on application and investigated effects of the panel forming.

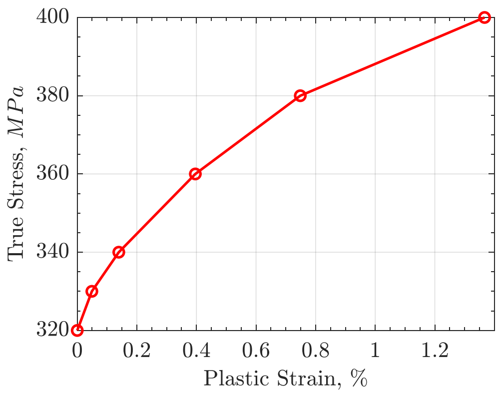

Fig 4 True stress-strain curve of the initial plastic region of aluminum D16chT (analog to Al 2024). The strain range is selected to be sufficient for modeling the forming process at the highest selected load in the study

To allow solver convergence in the simulation, weak spring function was utilized for simulating the bending of the middle rib. However, it was insufficient to prevent numerical solution instability for simulating the bending of the rest of the ribs. Therefore, the weak spring function was replaced by elastic support applied to the bottom and sides of the panel to enable stable numerical convergence. The stiffness of the elastic support was adjusted to 100 kN/m^3 for which the difference between solutions with the weak spring function and elastic support was less than 1 % for the middle rib.

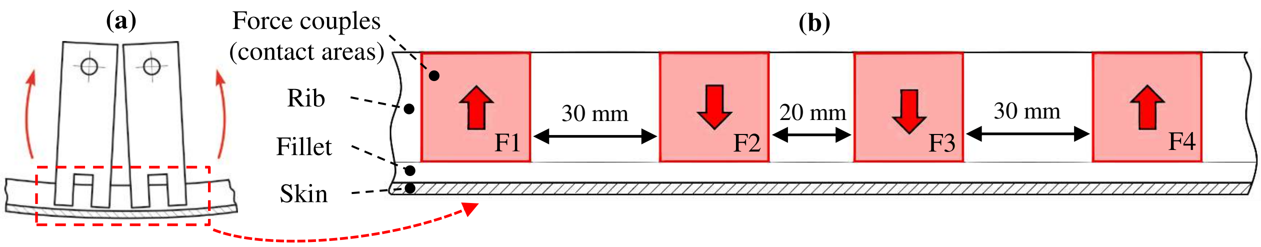

Fig 5 (a) Schematics of the experimental tool fixed on the rib and applying bending moment to the rib; (b) magnified view of the monolithic panel and force couples applied to a rib in the contact areas of tool grips. Force couples are named for further reference

In the local deformation forming process, a single tool impact is accomplished in three steps: gripping a rib with the tool, bending a rib, and unloading. As the maximum and residual values of deformation and stress are of interest, the first step is dropped in the numerical analysis.

4. Results

This section demonstrates the results for deflections, stresses, and strains during and after loading (residual values) for the panel at different conditions.

4.1. Numerical Model Validation

As the first step, the model was validated by comparing the deflection of the panel under the load of 14 kN force couples of the designed tool applied in the center of the middle rib (**Fig *6***a). The deflections under the load rather than residual deflections were used due to their higher magnitude and the intention to validate the deflection produced by the single impact of the tool. The magnitude of the force couples is selected such that the panel experience a considerable amount of plastic deformation in order to validate the selected material plastic model as well. As **Fig *6***b demonstrates, the experimental deflection contour of the middle rib largely matches the numerically obtained shape. The difference between the experimental and numerical results is due to an unsymmetric shape of the experimentally formed panel. Therefore, the deviation of results comes mostly from the imperfect initial flatness and sizing of the tested panel.

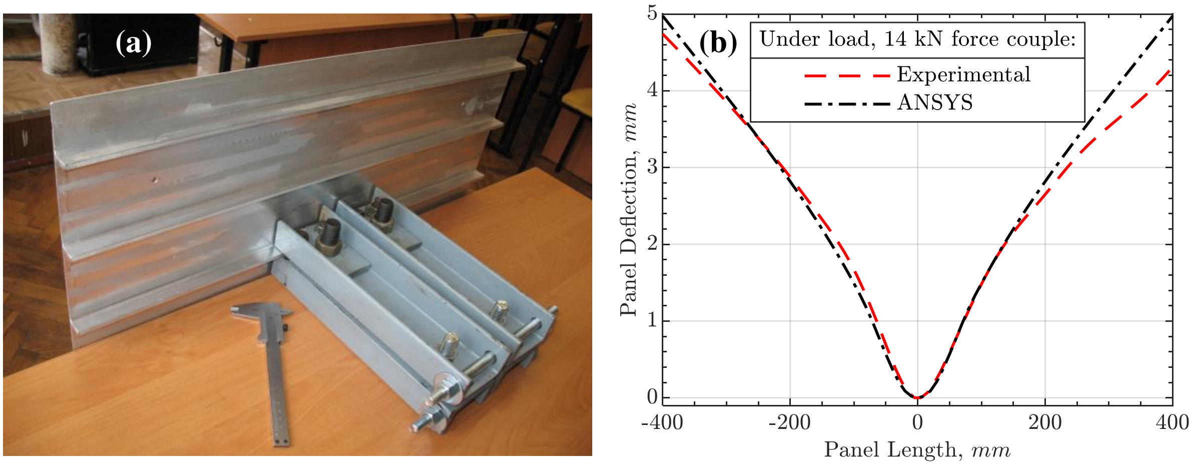

Fig 6 (a) Designed tool fixed in the center of the panel's middle rib and (b) experimental and numerical deflections of the panel along the middle rib under the load of applied force couple of 14 kN. The measurement of the panel deflection was performed with 6-axis probing system ROMER Absolute Arm

4.2. Single Bending of the Middle Rib

Figures 4a and 4b show the total equivalent Von Mises strains during step two (under the load) and step three (after unloading), respectively. The deflections of the panel are scaled for visualization purposes. As the figures depict, the deformation occurs locally in the target area of the loaded rib only. Particularly, total equivalent deformation has an average value of approximately 0.5% (and picks at almost 0.53%) in the top portion of the rib under the load (**Fig** *7*a). When unloaded, only that top portion of the rib is permanently deformed with an average strain value of approximately 0.05% and a maximum value of 0.0834% (**Fig** *7*b). In addition, residual elastic strains in the skin and adjacent ribs are an order of magnitude lower than the residual values in the loaded rib area. Thus, no plastic deformation is present in the skin or adjacent ribs (the dark blue region in **Fig** *7*b represents the material that occurred less than 0.01% of residual elastic strain). This emphasizes that the plastic deformation zone is small and concentrated in the vicinity of the tool grips impact. Moreover, the strains in adjacent ribs and skin are minor even under the load of the tool, suggesting that the forming process by local deforming is less affected by the adjacent structural elements of the panel due to the absence of direct tool impact on the adjacent areas. This makes the location deformation forming approach more beneficial as it adjusts easier to various configurations of ribbed panels.

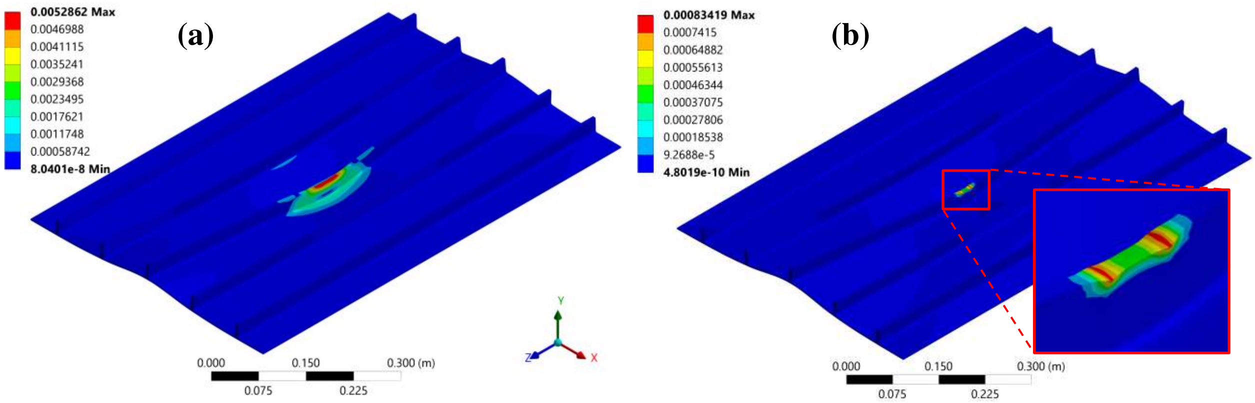

Fig 7 Total Von Mises strains for the forming of the middle rib of the stiffened monolithic panel by 10 kN force couples: a – during the loading, b – after unloading (residual strain)

4.3. Local Effect of the Tool on a Panel Rib

The above figures demonstrate the maximum values of total Von Mises strains in the panel under the load and their residual values. However, local stress distribution in the area of the tool impact is of great interest due to its effect on further panel strength during its operation. Moreover, having applications in bodies of aerospace and marine vessels, stiffened monolithic panels dominantly operate in tension/compression modes. Therefore, the local residual stress distribution is studied in terms of residual normal stresses and is shown in **Fig** *8*. Two magnitudes of force couples were selected to show the dynamics of the residual stress distribution as the tool impact intensity varies. **Fig** *8*a shows the results of applying 10 kN force couples, which results in strains just above the yield point and, therefore, low residual normal stresses. As stated before, the residual stresses are dominantly located in the top portion of the rib. However, two local compressive (shown in blue) and tension (shown in red) areas are clearly seen. Particularly, the residual tensile stresses concentrated on the top of the rib and maximum values near the edges of the inner grips of each tool, i.e., force couples F2 and F3 (**Fig** *5*b for reference). Meanwhile, the residual compressive stresses, formed during the material's unloading and elastic recovery, concentrate right below the areas with maximum tensile stresses, i.e., on the top of the F2 and F3 force couples' contact areas. Due to the panel skin-rib deformation pattern, high tensile stresses in a small part of the rib are balanced by low compressive stresses in the bottom part of the rib and skin. This explains a relatively small magnitude of stress in the local compressive area. Meanwhile, tensile stresses concentrate on the upper surface of the rib, having much higher values. It can be seen that the tensile stresses between the local tensile areas are distributed much more uniformly and possess values close to expected. Considering the pick tensile stresses are almost twice larger than the uniform compressive stresses, a design of the tool's grips that create a more uniform stress field can be the objective of future work.

Similar to **Fig** *8*a, **Fig** *8*b shows the residual normal stresses in the rib upon applying 12 kN force couple. The overall stress map has a similar appearance; however, the stressed areas and the value of stresses are greatly increased for both tensile and compressive zones. Secondly, the concentration of tensile stress is now more gradual along the rib as well as through the rib height. Last but not least, stresses in the skin, even on its inner surface, are practically unchanged. The overall tendency of accumulating residual stresses in the rib rather than the skin is beneficial for the panel strength in most applications from the perspective of fatigue strength propagation, stress corrosion, etc. [19,20].

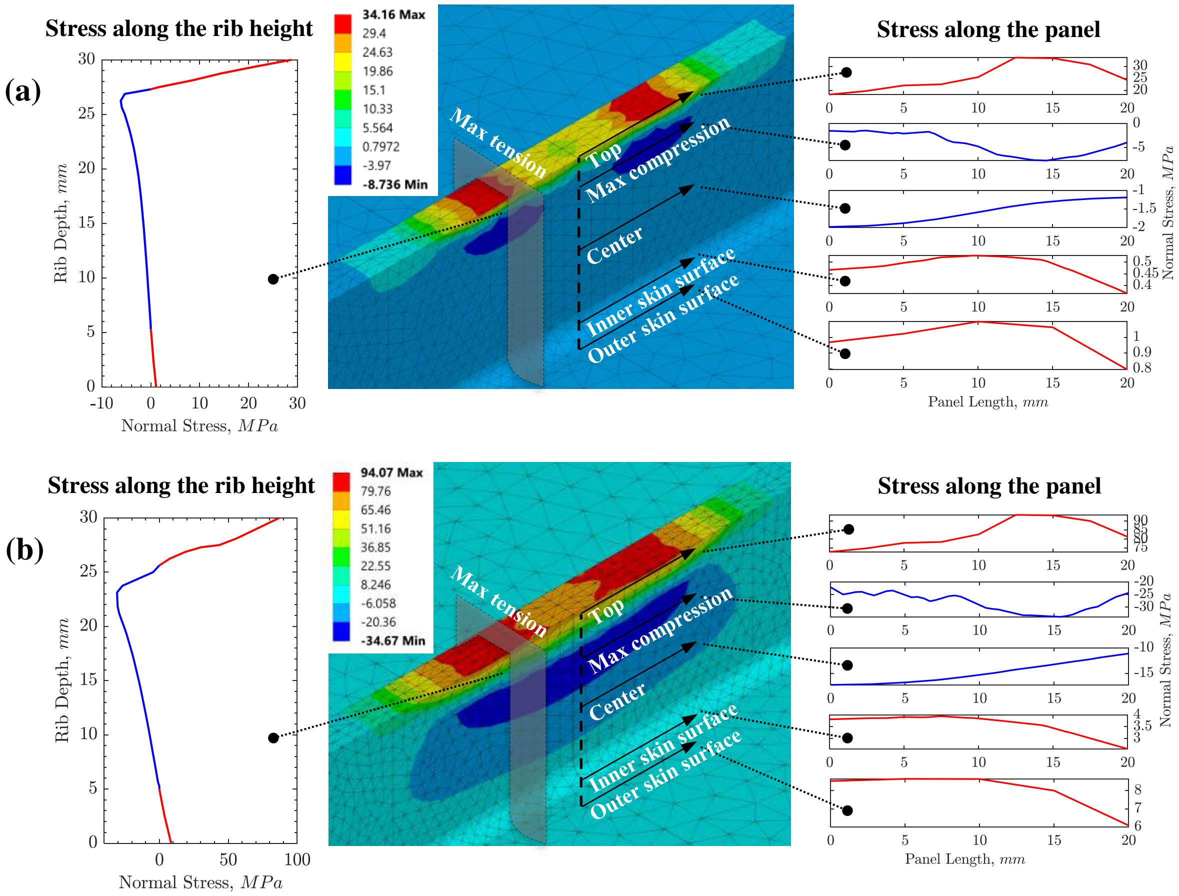

Fig 8 Residual normal stress [MPa] distribution in the middle rib after a single impact of the tool with the (a) 10 kN and (b) 12 kN force couples

4.4. Tool Force

The force applied during forming is an important factor driving manufacturing efficiency and final product quality. Therefore, residual deformation is studied for a single impact of the tool with different magnitudes of the force couples. Fig 9 compares the two residual equivalent strains, plastic and total, in the central portion of the middle rib between the concentrations of highest tensile stress (Fig 8) to correlate average strain values in the rib upon forming. Moreover, the long 3 m panel is also modeled to demonstrate the dependence of tool force on panel length. Although the panels possess the same cross-section, some deformation differences are noticed. While total deformations under the loading differ by just less than 1%, residual total and plastic strains have much higher percentage differences. This effect is seen as the forming process occurring at moderately low strains above the material yield point, exaggerating the difference between the short and long panels' behavior. Hence, the effect of the panel aspect ratio is important and must be taken into account when adjusting the number of tool impacts and force couples' magnitudes.

To lower the panel length effect on a local deformation process, the impacts should deform the panel with the limited plastic deformation in a rib. In addition, a small amount of deformation applied by each tool impact allows to avoid numerous possible forming defects in the panel [21], improve the forming tolerance, and maintain the surface quality. However, a larger amount of impact is required to reach the same final curvature for the panel, which negatively affects forming efficiency. Therefore, a range from 0.1 to 0.2 percent of residual plastic deformations during each local impact of the tool is selected in this study. As a result, a force couple magnitude of 12 kN is used for the rest of the analysis in this study to provide more practical results.

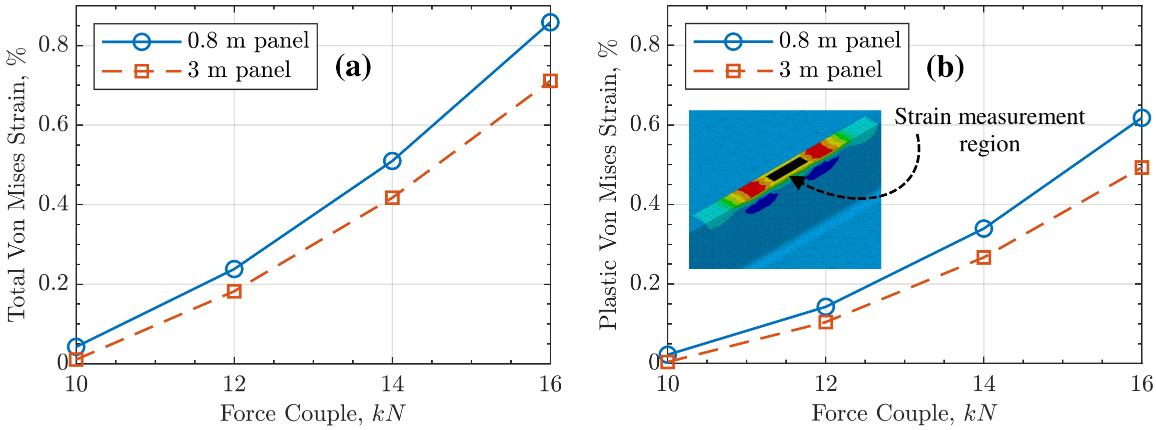

Fig 9 (a) Total and (b) plastic Von Mises strains at different impact loading for the short and long stiffened monolithic panels after unloading (residual strain)

4.5. Effect of Panel Length

As stated in the Introduction, the forming of oversized panels often appears to be challenging for numerous forming techniques. Therefore, a longer 3 m stiffened monolithic panel with the same cross-section is also numerically analyzed for the final deflection after forming. Fig 10 presents residual deflections after the unloading measured along the top surface of the middle rib for both short and long panels. Although the deflection of the panel tips seems close for both panels, the primary criterion is the panel curvature. As such, the curvatures of the short and long panels are considerably different, with the short panel bent more. The length itself has no effect on the panel's bending stiffness, and gravity is not considered. Nevertheless, the longer panel provides more space for the load to be carried by adjacent skin and ribs. Therefore, the stiffening effect of the longer panel comes from a better load redistribution.

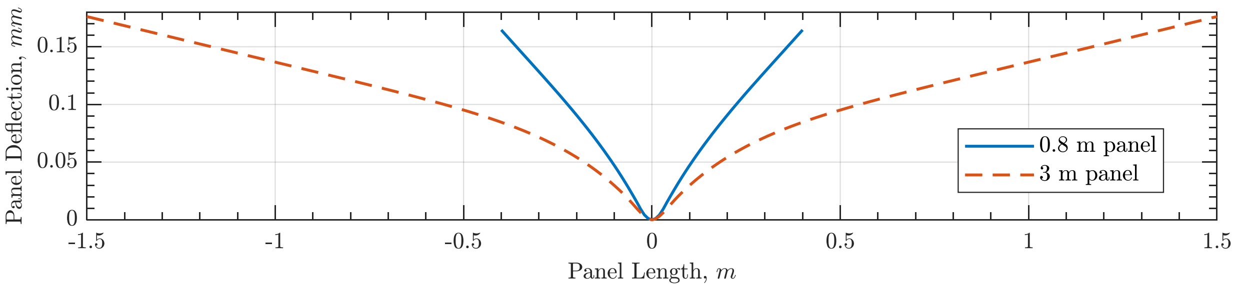

Fig 10 Residual deflections along the central rib for the short and long panels formed by 12 kN force couples

4.6. Effect of Finite Panel Width

Besides its length, the panel's width also affects the forming process. Particularly, when other than middle ribs are formed. To investigate the effect of the panel width, each rib of the 0.8 m long panel is formed by a single tool impact. **Fig *11*** demonstrates the resultant total Von Mises strains measured at the uniform middle region between the tool grips. Two cases were analyzed for each rib in which either 10 kN or 12 kN force couples were applied. Firstly, larger residual total Von Mises strains are noticeable for ribs located further from the panel axis of symmetry. The effect is expected as less skin and adjacent ribs resist the applied load. In other words, load redistribution to the adjacent skin and ribs happens less for the side ribs than for the middle rib. Secondly, the effect is greater for the case where 10 kN is applied, which again highlights the importance of selecting an optimum force couple load. A larger force couple magnitude results in a smaller difference between the ribs' deformation, i.e., a smaller effect of the finite panel width. The performed analysis suggests that the force couples' load can be carefully selected to obtain equal deformation of all the ribs in the panel, which can be hard to achieve in certain forming methods.

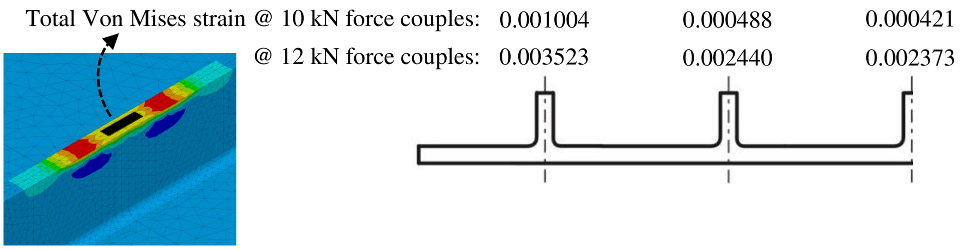

Fig 11 Effect of finite width of a stiffened monolithic panel on total Von Mises strains obtained by applying 10 kN and 12 kN force couples in the center of each rib. Three out of five ribs with corresponding strains are shown due to the panel symmetry

4.7. Successive Local Deformations

As the last objective of the study, the successive local deformation process is studied for the designed forming tool. First, successively forming each rib in the middle is considered and compared to the previously analyzed case of individually forming each rib. The successive forming was performed from left to right rib. **Fig *12*** shows the average values of the residual total Von Mises strain in each rib after applying force couples of 10 or 12 kN. When comparing the strain in the first rib with the strain in the fifth rib, and similarly the second and fourth ribs, the small difference in the values is obvious for both load cases. Accordingly, the residual deflections and strain of the previously formed ribs did not have a large effect on forming process of the subsequent ribs.

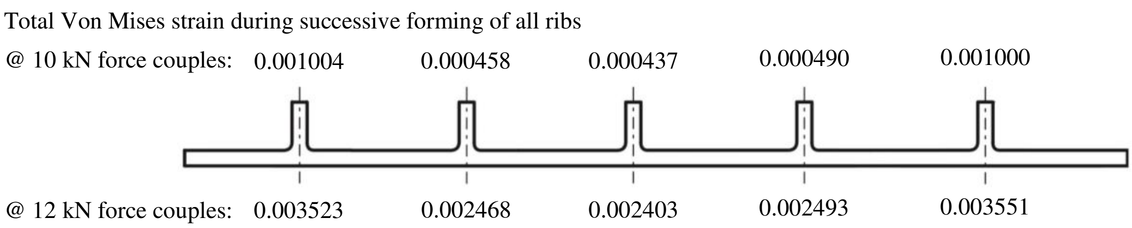

Fig 12 Successive forming of all five ribs of the panels by applying a single impact with magnitude of 10 kN or 12 kN force couples in the center of each rib

The second type of successive local deformation forming is forming of one rib with numerous tool impacts. Thus, a middle rib is deformed by seven evenly spaced tool impacts of 12 kN force couples. The residual deflection along the rib is measured and shown in **Fig *12*a**. As can be seen, just seven impacts result in a continuously formed rib shape and tip deflections of just under 1 mm with a limited smoothness of the panel. Residual normal stresses are also studied and shown in **Fig *12*b-c**. In analogy to the final panel width effects, the rib portions closer to the panel edges underwent larger deformation due to the lower stiffening by the adjacent skin and ribs. Therefore, adjusting the tool impact load and consequently the number of impacts to maintain the desired panel deflection is necessary to even the residual stress profile and improve the shape smoothness of the panel. Lastly, **Fig *12*c** also demonstrated residual normal stresses on the exterior side of the panel skin. Although the stress pattern repeats the stresses in the rib, the stress values oscillate about zero and are virtually negligible.

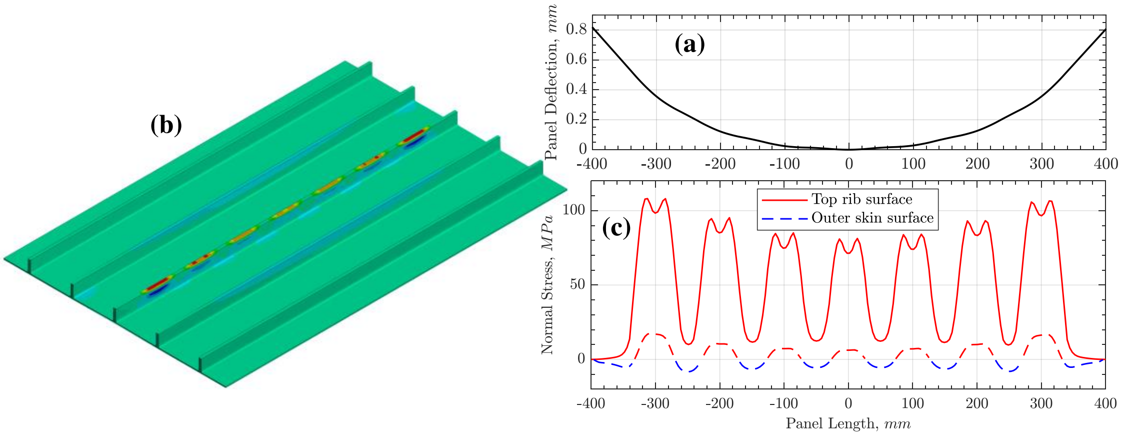

Fig 13 Successive forming of the middle rib by seven impacts of 12 kN force couples resulted in (a) residual panel deflection, (b) residual normal stress map and (c) its values

5. Conclusions

Accomplished numerical FEM modeling of the forming process of the monolithic stiffened panel facilitated the analysis of the local deformation forming technique with the designed tool. The results demonstrated and proved several important facts allowing to draw the following conclusions:

- The designed tool can effectively produce local deformation of the panel by dominantly deforming the rib of the stiffened panel with the minimized effect of adjacent ribs and skin.
- The residual strains/stresses concentrate in the top portion of the rib with their minimum values in the skin, which is advantageous for the strength of the panel under typical loads in aerospace and marine industries. As the impact load of the tool increases, stress distribution becomes more uniform in the rib but does not change considerably in the panel skin.
- The current design of the tool grips contact area leads to a stress concentration near their edges with stress values up to twice the average tensile stress on the top surface of the rib. Therefore, a thorough study of the grips' shape is required to lower the concentration of residual stresses.
- Longer panels possess considerably larger stiffness due to a more effective load redistribution to the adjacent ribs and skin.
- Remarkably larger deformations are achieved in the side ribs than in the middle ribs when equal impact was applied with the tool. Therefore, the impact intensity can be greatly lowered for the ribs further located from the center of the panel.
- Successive forming of different ribs of the panel proved their practical mutual independence.
- Successive forming of the middle rib by only seven impacts demonstrated adequate curvature of the rib and once again verified the stress distribution in the rib and panel skin.

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