Experimental Analysis of the Post-Buckling Behaviour of Compressed Stiffened Panel with Refill Friction Stir Spot Welded and Riveted Stringers

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ABSTRACT

The paper presents the results of research aimed at comparing two stringer joining technologies of stiffened panels. Experimental tests were carried out on the basis of uniaxial compression of thin-walled panels stiffened with two parallel stringers. The panels consist of a skin plate and stringers joined with two techniques: riveting and refill friction stir spot welding (RFSSW). The aim of the investigations was to determine the amount of the critical load, the character of the structure's work in the range of post-buckling behaviour and the mode of panel destruction. For deformation measurements, an optical scanner Aramis based on the digital image correlation (DIC) technique was used. The research conducted enabled the assessment of the effectiveness of the RFSSW technology of joining the semi-monocoque structures, taking into account the range of post-critical deformations caused both to the local and global loss of stability. The compression tests have shown that the plate with welded stringers with a spacing of 29.5 mm exhibits the ultimate load similar to the variant of the riveted panel. It was also observed that the nature and number of buckling half-waves depend on the applied load and spacing between connectors.

Keywords: friction stir spot welding; digital image correlation; thin-walled structure; EN AW-7075-T6 Alclad aluminium alloy, post-buckling analysis.

INTRODUCTION

Thin-walled stiffened structures are commonly used in aircraft construction. Most of the fuselages are based on a semi-monocoque structure, which ensures high stiffness and strength while maintaining a relatively low weight [1, 2]. Structures of this type consist of a skin which transfers some of the loads on the structure, while the skin is reinforced and stiffened with stringers and frames, which enables such a thin-walled structure to carry heavy loads [3–5]. In the construction of aircraft elements, it is allowed for the discussed semi-monocoque structures to transfer

the loads also after their buckling in the elastic range. Importantly, the structure in post-buckling states behaves in a stable manner, which is a significant advantage of such solutions [6]. Post-buckling states are an important scientific issue undertaken by many authors of research papers. Vashist [7] showed in his work that the classical linear buckling theory cannot be used to describe post-buckling phenomena. In the research of semi-monocoque, the classical buckling criterion cannot be used either. Allowing the structure to operate in post-buckling states is particularly advantageous in aviation because it allows weight reduction. Post-buckling analysis requires the use

of nonlinear analysis based on large deflection theory. There are a number of papers describing experimental studies of behaviour in post-buckling states of thin-walled structures [8]. However, a very effective tool for analyzing such phenomena is the finite element method (FEM). A detailed analysis of the post-buckling states occurring in the thin-walled semi-monocoque structure with the use of FEM was carried out by the authors of the study [9]. They found that the derived stress-strain curves under different values of loading have a significant effect on the post-buckling response of stiffened panel.

Kumar et al. [10] and Khedmati et al. [11] described detailed experimental analyzes of the phenomena occurring in post-buckling states for structures made of aluminium alloys. It should be noted that the effectiveness of structures in terms of stiffness and strength is influenced by a number of factors, the main of which are: properties of the skin material and stiffening elements, the technology of their joint, the geometry of the structure is also important issue. In the aerospace industry, these structures are typically fabricated from aluminium alloys or from fiber reinforced polymer (FRP) composites. Various technologies of joining skin with stiffening elements are used, such as: riveting, laser beam welding, adhesive bonding, and more often the technology of friction stir welding [12] is being considered. Regardless of the manufacturing technology, it is necessary to ensure high-quality joints and their resistance to extreme operating conditions. Due to the operation of airplanes in various conditions, as well as the very specificity of the flight, the joints must meet a number of strength, fatigue and corrosion resistance conditions [13, 14]. It should be noted that aluminium alloys used in the construction of aviation structures, these are mainly 2xxx series and 7xxx series alloys, are difficult to weld due to alloying elements. All this means that the technologies of joining the stiffening elements in semi-monocoque structures must meet a number of requirements.

Figure 1 shows a typical semi-monocoque construction consisting of skin and stiffening elements, i.e. stringers and frames. Stiffening elements shape the skin and transfer the loads acting on the fuselage [10]. Riveting is the most common method of joining stiffening elements to the skin. Despite a number of advantages, the rivet holes are notches in the structure, and the rivets themselves add additional weight to the structure.
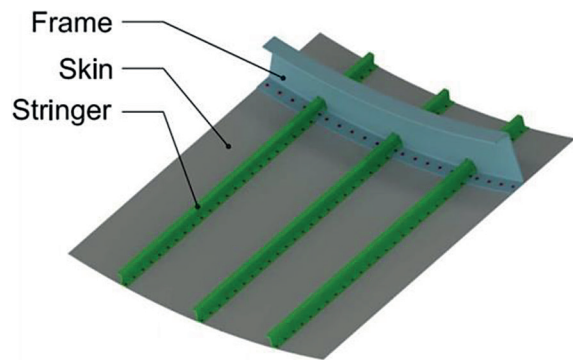

Fig. 1. The fragment of the stringer-stiffened fuselage

Therefore, alternative joining technologies are being used more and more. One of them is laser beam welding. Although it is an effective technology that generates a very limited heat-affected zone (HAZ), which is extremely important in the context of thin-walled structures, welding with this method requires advanced and expensive equipment. Hence, it is not a widely used technology. Adhesive joints are used primarily in the case of structures made of FRP composites, these technologies require energy-consuming autoclaves, which also, for economic reasons, limits the universality of the technology.

A promising method of joining unweldable aluminium alloys is friction stir welding (FSW). The authors of [15–17] presented a series of experimental studies of stiffened thin-walled structures in which the stiffening element was welded using the FSW method, thus demonstrating the effectiveness of this technology. A variation of FSW linear welding is the spot welding, i.e. refill friction stir spot welding. Importantly, this method consists in joining the plasticized material, it does not melt, so the heat-affected zone is limited to a small area around the weld. Much research has been done on the properties of RFSSW joints. Shen et al. [18] conducted a series of experimental studies aimed at showing the influence of the RFSSW welding parameters on the mechanical properties and microstructural properties of welded joints of sheets of aluminium alloy EN AW-7075-T6. This paper shows, above all, how sensitive the welding process is to the individual parameters that determine the properties of the joints. The authors of the papers [19, 20] have also described the research on stiffened aircraft structures in which RFSSW welding was used as the joining technology. These papers discuss the effects of RFSSW welding parameters on the

static shear strength of joints of aluminium alloy sheets, as well as on fracture mechanisms.

Due to the nature of the exploitation of aircraft structures, the joints of the stiffening elements are exposed to fatigue loads, hence it is extremely important to undertake this research topic in the context of welded joints. The influence of the RFSSW welding process parameters on the fatigue strength and the fatigue fracture mechanism for the joints of sheets made of the EN AW-7075-T6 alloy was carried out by Kubit et al. [21]. The aim of this work was to conduct experimental comparative studies of panels stiffened with stringers joined by riveting and by RFSSW welding. This problem makes it possible to evaluate the behaviour of plates stiffened with welded stringers subjected to uniaxial compression in relation to panels with riveted stringers, which are very well known. The aim of the investigations was to determine the amount of the critical load, the character of the structure's work in the range of post-critical deformations and the mechanism of its destruction. The research conducted enabled the assessment of the effectiveness of the RFSSW technology of joining the elements of semi-monocoque structures, taking into account the post-critical panel deformation.

EXPERIMENTAL

Material

In the research, panels stiffened with two parallel stringers were used. Both elements, i.e. skin and stringers, were made of EN AW-7075-T6 aluminium alloy, it is a material commonly used in the construction of aircraft structures. The chemical composition of this alloy (wt.%) is presented in Table 1. Two different sheet thicknesses were used to prepare the stringer-stiffened structure. The S-shaped stringer has been prepared using

sheet with a thickness of 1.6 mm. The skin thickness was 0.8 mm. This configuration is typical for an airplane fuselage structure, according to the Figure 1. To join the skin with stringers, the rivets made of AlCu2Mg aluminium alloy were used, whose diameter was 3mm. The mechanical properties of the material used were determined on the basis of tensile test carried out in accordance with the recommendations of the ISO 6892-1:2016 standard [22]. Three samples were tested at room temperature. Table 2 presents the averaged values of specific mechanical parameters.

Stringer-stiffened panels

The shape and dimensions of stringer stiffened panel are shown in Figure 2. Two stringers were used to stiffening the skin. Both welded and riveted panels were joined in the configuration of a single line lap joint. The spacing p (Fig. 2) between connectors corresponds to the standards used in the aircraft industry. Two methods were used to fabricate stringer stiffened panels: riveting and RFSSW. Riveting was conducted with air riveting hammer. The welding process was conducted at Belgian Welding Institute using RPS100 VA11 machine by Harms & Wende (Hamburg, Germany). Joints were made with different rivet/spot spacing: riveted structure: $s = 23.5$ mm; welded structure: $s = 29.5$ mm and $s = 44.25$ mm.

The RFSSW process realised using nonconsumable rotating tool (Fig. 2) consists of four stages [17]. In the first stage the pin and sleeve are positioned on the stringer surface and rotate to generate frictional heat. Then the sleeve penetrates the both materials of stringer and skin, and pin retracts. In the third stage the movement of the sleeve and pin is reversed. The sleeve retreats and pin presses plasticized material into an exit hole. The rotational action of the tool causes the mixing of plasticised material which result in formation of solid-state weld. Finally, the tool is retracted

Table 1. Chemical composition of EN AW-7075-T6 aluminium alloy (wt.%)

Al	Cu	Mg	Zn	Mn	Fe	Si	Ti	Other inpurities
87.1–91.4	1.2–2.0	2.1–2.9	5.1–6.1	0.30	0.50	0.40	0.30	0.15

Table 2. Basic mechanical properties of EN AW-7075-T6 aluminium alloy

Parameter	Ultimate Tensile Stress R_m, MPa	Yield Stress $R_{p0,2}$, MPa	Elongation A, %
Value	482.6	413.7	7

from the stir face of stringer. The welding process is realised in the following conditions: welding time 3.5 s (plunge time 1.5 s, retraction time 1.5, dwell time 0.5 s); plunge depth 1.9 mm; tool rotation speed 2000 rpm. The stringer-stiffened panel was tested in a uniaxial compression strength test using universal uniaxial testing machine Zwick Roell Z100. The dimensions and configuration during the panel test are shown in Figure 3.

Deformation measurement

Digital Image Correlation is an experimental optical-numerical technique that allows determining the deformation fields of the three-dimensional structures. The advantages of this method include the high accuracy of measurements, enabling the determination of both displacement and deformation fields. Moreover, the measurements may be conducted on real structures during their operation [20]. The ARAMIS system was used to analyse the panel deformation during the compression test. The ARAMIS is non-contact measuring system which consists of two main components. The first is the device called a scanner, consisting of two high resolution digital
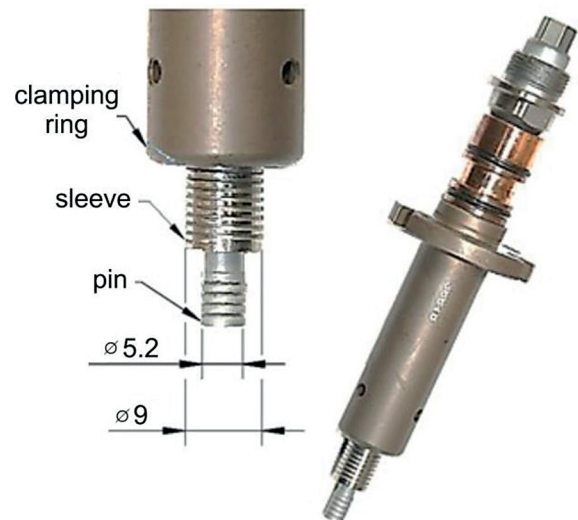

Fig. 2. Geometry and dimensions of RFSSW tool

cameras positioned in relation to each other in order to build a spatial image. The system enables taking images at a maximum speed of 25 frames per second. The second art of the ARAMIS system is a computer with a special software for numerical processing photos taken during the research. The research object should be suitable prepared. Preparatory work involves covering the surface
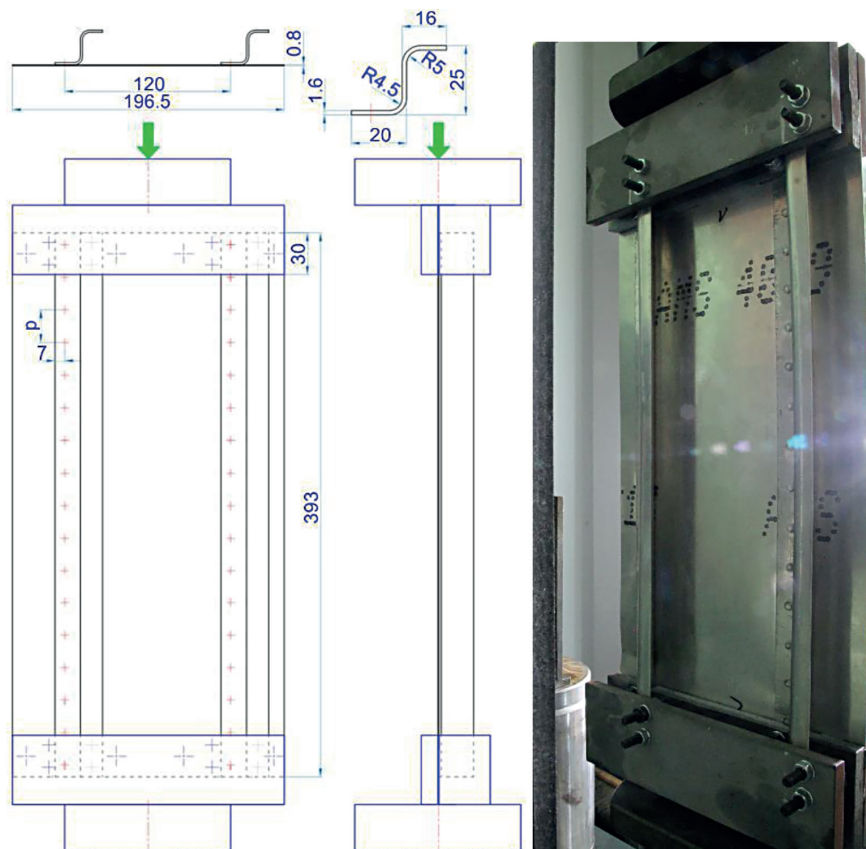

Fig. 3. Dimensions of the stiffened panel subjected to uniaxial compression test and the experimental setup

of the panel with white paint. Then random pattern of black spots is applied. Selection of the spot size depends on the dimensions of the object being examined and the optical properties of the measuring apparatus. The DIC analysis consists of taking a series of images of the object in subsequent loading phases. DIC of images from both cameras allows to specify the position of each pixels in three-dimensional space. Then the images are divided into deformation meshes. While loading a panel, due to deformations of its surface, the spots in each part of the mesh change their position relative to each other. It is the basis for calculating the deformations in relation to the reference position.

Fig. 4. Results of compression tests

RESULTS AND DISCUSSION

The results of the uniaxial compression tests are shown in Figure 4. The riveted and welded variants of the stringer-stiffened plate with a spacing of $s = 23.5$ mm and $s = 29.5$ mm, respectively, exhibit similar load characteristics up to force equal of approximately 42 kN. A further increase in the displacement of the grip of testing machine caused a fast reduction in the value of the loading force for the welded panel. This drastic loss of panel stiffness could have been the result of weld damage. The load characteristics of riveted panel did not show a local decrease in a force value. After reaching a maximum force value of 43.2 kN, the force slowly decreases until the panel was destroyed. The relatively small spacing between welds ensured high stiffness of the panel. So, until the loss of stability none of the rivets was damaged. A higher compression load can cause higher clamping pressure on the panel [23]. In this case, this may tend to make it easier to transfer the load from the rivet to the following rivet. A welded panel in a variant with a spacing of $s = 44.25$ mm is characterized by the lowest stiffness. The first weld was destroyed at a displacement of 3.5 mm. However, further loading of panel even increased their stiffness. When displacement of the grip of testing machine reached 4.2 mm the localization of the deformation occurred.

The deflection of the stringer-stiffened panel has been measured by ARAMIS program at different load levels. Figure 5 presents the development of the displacement pattern for the riveted variant ($s = 29.5$ mm) of the panel. The destruction modes of the panels have been presented in Figure 6. Initial buc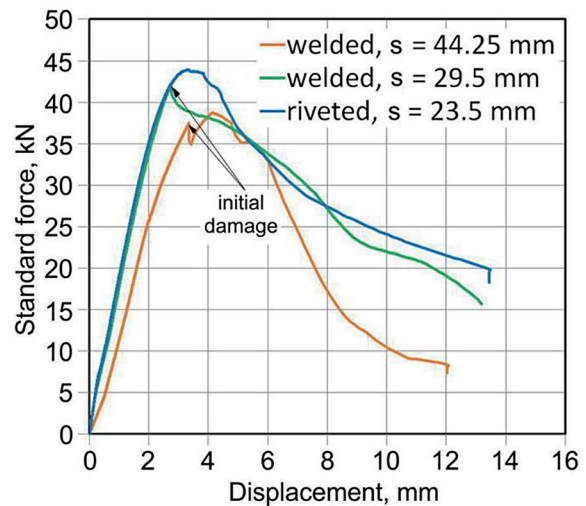kling pattern exists in a central part of the panel. Increasing of the load causes a change of the buckling pattern into a pattern with 5 half waves immediately after initial buckling. No further changes of the buckling pattern occur up to the global buckling in the middle part of the panel (Fig. 6b). Due to the lower stiffness of the welded panel with a spacing between welds $s = 44.25$ mm there was a more distinct decreasing of transfer of the load from the skin to stiffeners than in the case of the welded panel with a spacing $s = 29.5$ mm. So, the buckling of the skin between welds was observed. Similar to the case of the welded panel with a spacing $s = 29.5$ mm, for the welded panel with a spacing $s = 44.25$ mm plate the global buckling was observed in the middle part of the panel (Fig. 6a). Characteristically, the deformation of the panel results in two dominant half-waves.

For panels with welded stringers, it was observed that under the influence of the maximum load values, the welds were damaged due to peeling under normal stresses caused by local buckling between the spots. As a result of these stresses, the most loaded welds were damaged due to circumferential cracking of the skin around the weld. As a result of the destruction of the spots, the entire panel failed with a load lower than in the case of the riveted panel. It should be noted that the peel phenomenon could be the result of incorrectly selected parameters of the RFSSW welding process, it should be remembered that a plunge depth of 1.9 mm was used here. Although the selected parameters ensure high shear strength, in the final stage of the panel loading, normal stresses loading the spots had a
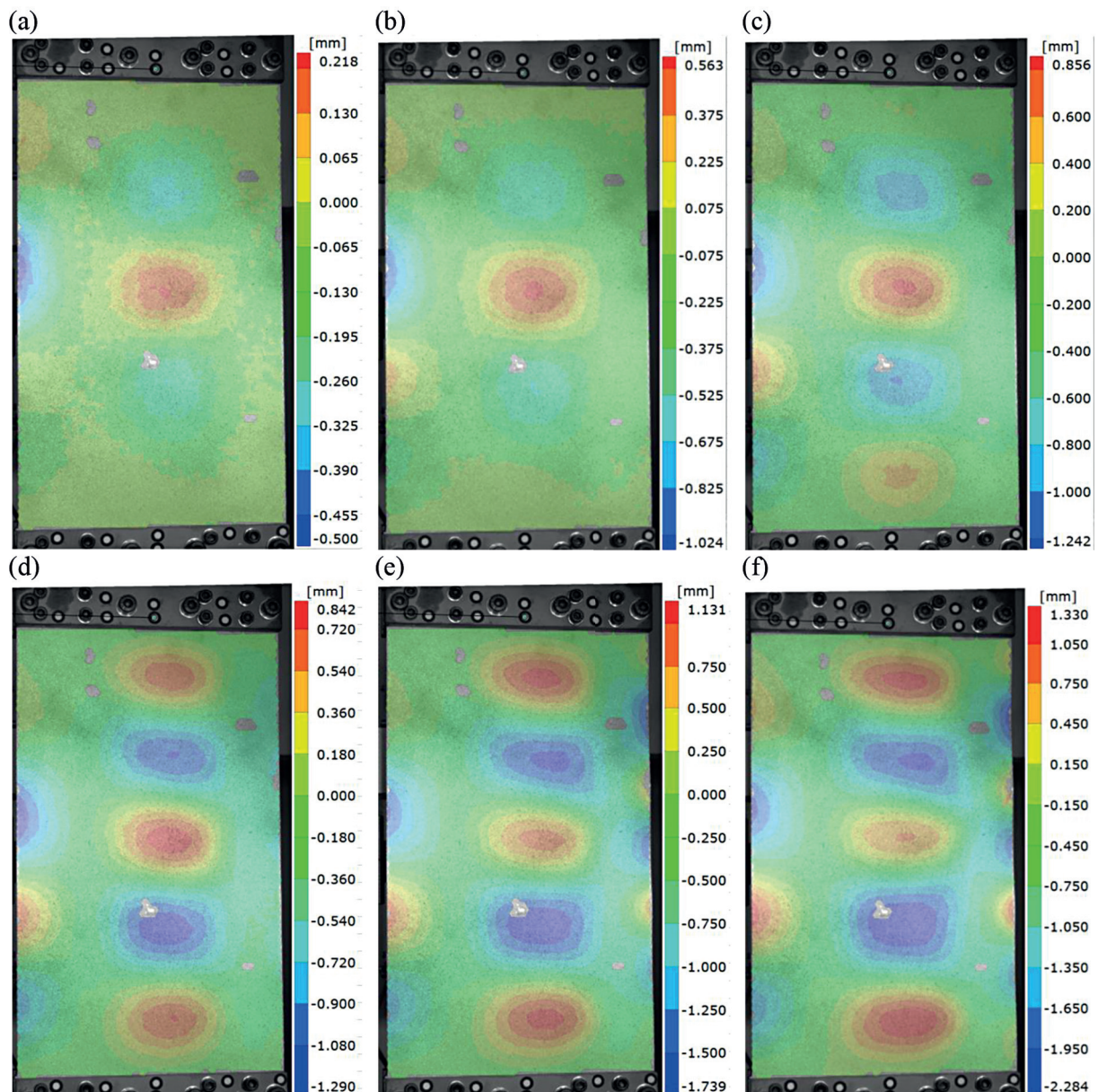
Fig. 5. Deflection of the welded panel (s = 29.5 mm) loaded by a compressive force of a) 1822 N, b) 3277 N, c) 6317 N, d) 8325 N, e) 12420 N and f) 16003 N obtained using ARAMIS

significant share. The peel sensitivity of RFSSW welds may be influenced by the structural notch observed in the weld structure (Fig. 7), which is an effect of the high plunge depth value. This may be the reason why, under the load in the final stage of compression of the panel, cracking occurred in the weakened perimeter of the skin sheet around the weld.

Figure 8 shows the evolution of the half waves in welded panel (*s* = 29.5 mm) in the range of grip displacement between 0.2 and 0.7 mm. It was found that deflection in the middle part of the panel does not change (3rd half wave in Fig. 8). The deflection of the rest waves increases with the movement of the upper grip of the testing machine. In the case of the riveted variant of the panel loaded up to approximately 3600 N no clear deformation in the area between stringers was observed (Figs. 9a, b). Further increase of the compressive force causes formation of three main half waves. No further changes in the number of half waves up to the global buckling of the panel were observed (Fig. 6b). Global buckling of the panel is localised in the path between two destroyed rivets (Fig. 8c). At small values of compressive force in both variants of the panels there is a local loss of stability of the skin at the vertical non-supported edges of the panel.
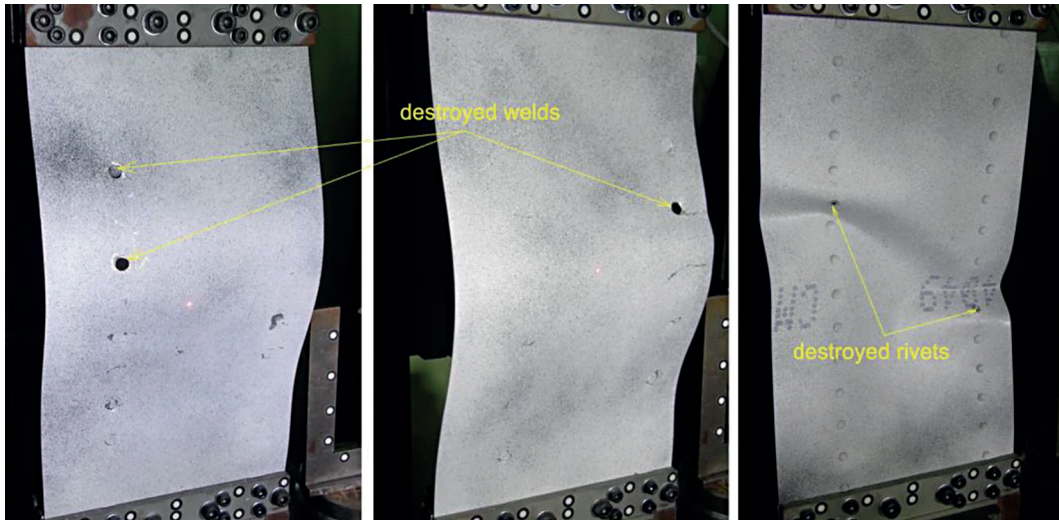
Fig. 6. Views of the panels after compression tests: a) welded variant with *s* = 29.5 mm,
b) welded variant with *s* = 44.25 mm, c) riveted variant with *s* = 23.5 mm
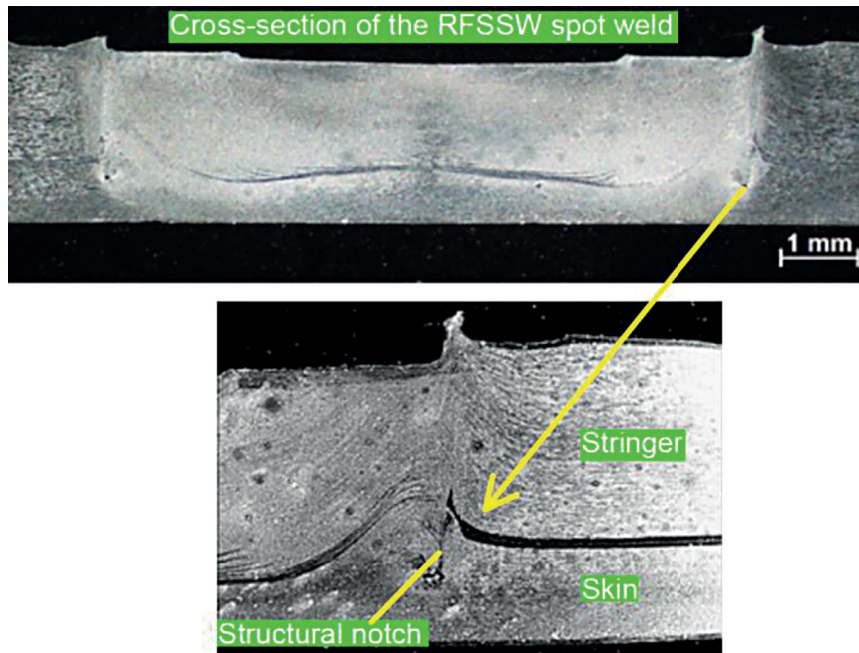

Fig. 7. Cross section macrograph of the RFSSW spot weld with the structural notch marked

CONCLUSIONS

Although riveted joints are a well-known technology and are effective in the construction of responsible aircraft structures, they have some disadvantages, which mean that alternative joining technologies are still being desired. One of the major disadvantages is that the riveted holes are stress concentrators. On the other hand, the rivets themselves increase the weight of the entire structure. RFSSW is relatively a new welding method and can be considered as an attractive and alternative to riveting technique of joining aluminium alloys in aircraft industry. The aim of the investigations presented in this paper was to determine the amount of the critical load, the character of the structure's work in the range of post-buckling behaviour of stringer-stiffened panels which elements were joined using both riveting and RFSSW techniques. The strength tests have shown that the plate with riveted stringers (*p* = 23.5 mm) exhibits maximum ultimate load. The welded panel with the spacing *p* = 29.5 mm exhibits ultimate load smaller at 5% compared to the riveted variant. But this may be the reason for incorrectly selected parameters of the RFSSW welding process. It should be emphasized

that this welding technology is very sensitive to the parameters that determine the strength of the joints. Increasing of the weld spacing to the value of $p = 44.25$ mm cause the weld failure before the loading force reached maximum value. The buckling modes revealed by DIC system are in a good agreement with the experimental observation. The results presented in this paper showed that RFSSW welding can be successfully considered as an alternative to riveting of thin-walled stiffened structures. However, the spacing between welds must be appropriate. It should be also noted that RFSSW is characterized by lower labour consumption than a riveting technique and does not require pre-drilled holes in the elements to be joined. Such holes are a source of dynamic fatigue.
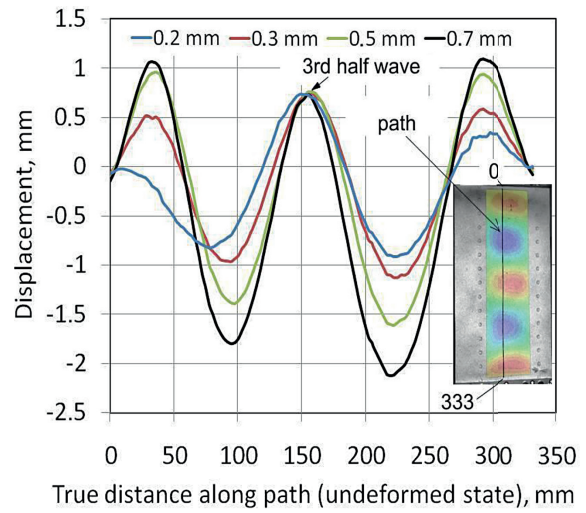

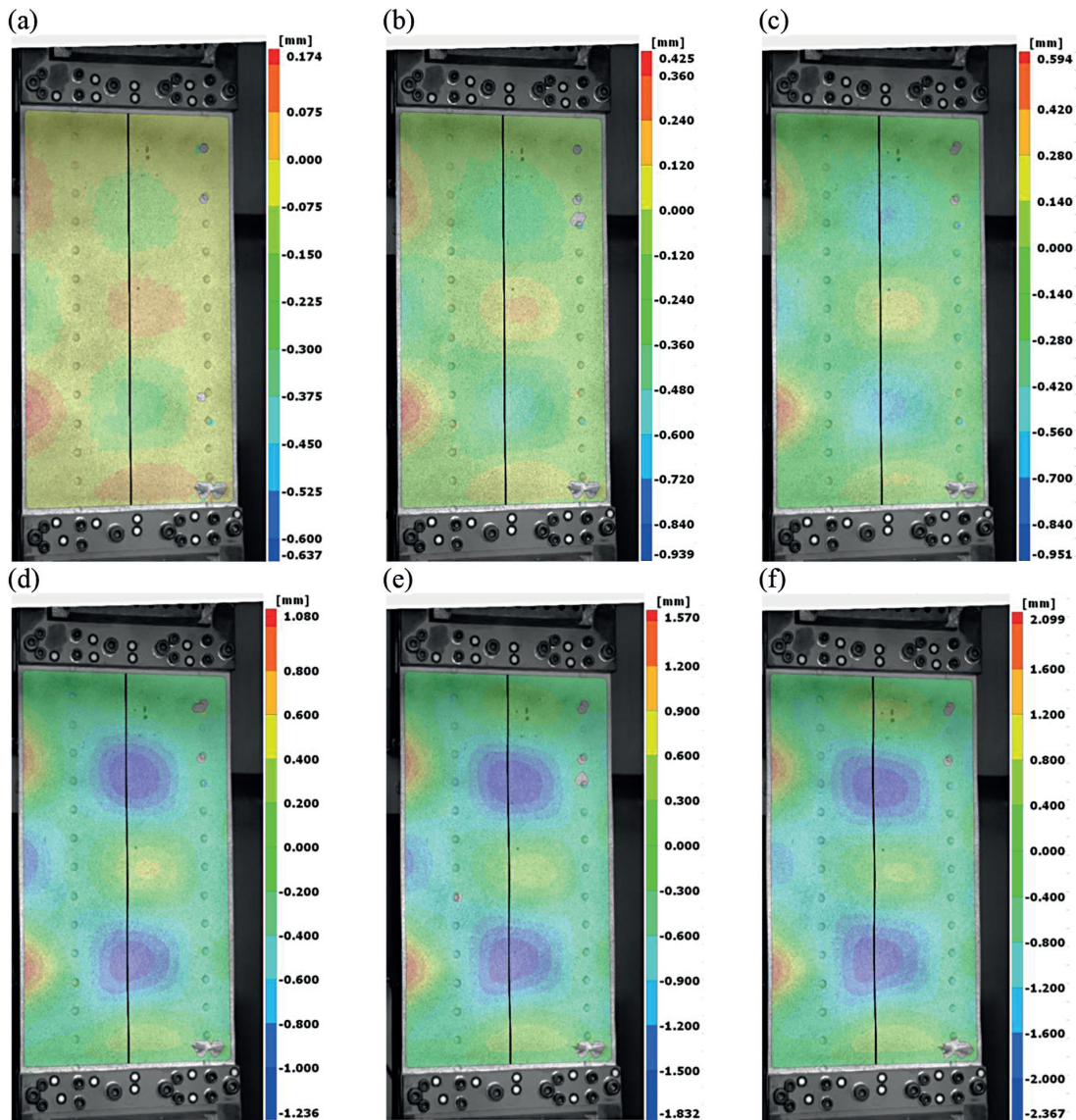**Fig. 8.** Defection of the welded panel ($p = 29.5$ mm)

Fig. 9. Deflection of the riveted panel loaded by a compressive force of a) 1587 N, b) 3622 N, c) 5004 N, d) 9503 N, e) 14499 N and f) 18967 N obtained using ARAMIS

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