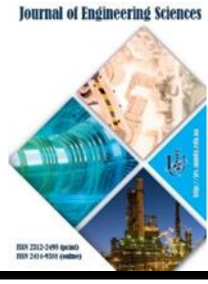
JOURNAL OF ENGINEERING SCIENCES

Volume 10, Issue 1 (2023)

Uysal M. U. (2023). Effects of cryogenically treated CFRP composite on the buckling behavior in the adhesively bonded beam. Journal of Engineering Sciences, Vol. 10(1), pp. D1-D7, doi: 10.21272/jes.2023.10(1).d1



Effects of Cryogenically Treated CFRP Composite on the Buckling Behavior in the Adhesively Bonded Beam

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Article info:	
Submitted:	March 7, 2023
Received in revised form:	May 5, 2023
Accepted for publication:	May 12, 2023
Available online:	May 15, 2023

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Abstract. Carbon fiber reinforced plastic (CFRP) composite materials have favorable mechanical and physical properties such as low density, high strength-to-weight ratio, high fatigue resistance and high creep behavior, and high stiffness. Thanks to these unique properties, they produce aircraft parts such as outer flaps, carry-through structures, and center wing boxes and automotive parts such as body panels, engine components, and structure members. However, studies have been continuously performed on improving the properties of CFRP composite materials. Recently, investigation of the effects of cryogenic (LN_2) cooling on the mechanical behavior and characteristic of these composite materials is getting a popular and important issue. In this sense, this study aims to examine the buckling behaviors of adhesively bonded beam-produced cryogenically treated carbon fiber reinforced plastic (Cryo-CFRP), CFRP, steel, and aluminum. Therefore, a new finite element model was adopted to evaluate the buckling capacity of Cryo-CFRP composite material in the adhesively bonded beam. The model is a supported adhesive beam subject to two opposite-edge compressions until the material buckles. The elastic, homogeneous adhesive was used in the assembly. Finite element models for the adhesively bonded beam having four different adherents (CRFP, Cryo-CFRP, steel, and aluminum) were established by ANSYS® software. The critical buckling loads of the adhesively bonded beam were predicted, and their mode shapes were presented for the first six modes. The effects of the usage of Cryo-CFRP on the critical buckling load were investigated. Among the adherents' materials, the highest critical buckling load was determined for Cryo-CFRP/Steel adhesively bonded beam as 23.6 N. This value was obtained as 22.3 N for CFRP/Steel adherent samples. Thus, the critical buckling load was increased by 5.6 % when one adherent steel was constant and the other adherent material changed from CFRP to Cryo-CFRP. Also, the critical buckling load increased by 3.7 % when using a cryogenically treated Cryo-CFRP/Aluminum couple instead of a CFRP/Aluminum couple in the sandwich beam. The findings demonstrated that the cryogenic treatment positively affects the buckling behavior in the adhesively bonded beam.

Keywords: buckling behavior, finite element method, process innovation, environmentally-friendly materials construction.

1 Introduction

Carbon fiber composites, particularly those with polymeric matrices, have become the dominant advanced composite materials for aerospace, automobile, sporting goods, and other applications due to their high strength, high modulus, low density, and reasonable cost [1]. For applications requiring high strength and stiffness, as required by aerospace applications, carbon fiber reinforced plastics (CFRP) made using carbon fibers for reinforcing plastic resin matrices have become popular because their properties make them especially attractive.

CRFP composites have been increasingly used in the aerospace industry to build more reliable and fuel-efficient aircraft. Currently, fuel cost is calculated to be around 32 % of the airlines' operating cost, whereas it was 14 % in 2003 [2]. Airlines have reacted to this financial pressure by replacing older aircraft with a new generation of aircraft that are more fuel efficient. This efficiency partly comes from the increased use of sophisticated materials [3].

2 Literature Review

Studies have been continuously performed on improving the properties of CFRP composite materials. Recently, investigation of the effects of cryogenic (LN_2 – Liquid Nitrogen) cooling on the mechanical behavior and characteristic of these composite materials is getting a popular and important issue. Cryogenic treatment studies the behavior of materials at relatively low temperatures and examines the use of cryogenic coolants. The advantages of using the cryogenic treatment and machining techniques over the conventional methods were summarized by Pušavec et al. [4]. Cryogenic coolants can considerably reduce the high temperatures generated due to the continuous friction between the tool and the workpiece [5]. The LN_2 is the most commonly used cryogenic coolant in machining applications [6]. The LN_2 is a non-flammable, non-toxic, environmentally friendly gas. It has also been that cryogenically treated parts have improved surface integrity and fatigue resistance [7]. Researchers have previously investigated the effect of using cryogenically treated materials. Most of the work was conducted on metals such as steel, nickel, and titanium alloys. Minimal work has been conducted on cryogenically treated composite materials.

Kim and Donaldson [8] studied the mechanical properties of carbon fiber, and exposure to cryogenic temperatures with load can produce an actual rate of damage accumulation in the composite which may alter their material properties. They claimed that thermomechanical properties, such as transverse modulus, shear modulus, transverse shear modulus, and transverse strength, increased when the temperature was reduced. Drilling experiments were performed under dry and dipped cryogenic conditions using solid carbide drills and investigated the mechanical behaviors of composite materials [9]. A temperature-dependent micromechanical model, including the law of temperature-dependent Young’s modulus of polymer, investigated the transverse mechanical properties of unidirectional CFRP composites at different temperatures [10]. The cryogenic temperature characteristic of several carbon fiber-reinforced composite materials was investigated and summarized in detail related to its mechanical and thermal aspects by Reed and Golda [11], who reported that Young’s modulus and tensile strength of carbon fiber-reinforced composites increase as the temperature decreases. The challenges related to cryogenic experimental testing and analysis were introduced. The behavior of composite materials at low and cryogenic temperatures and the mechanical properties of the composite were reviewed. The material properties addressed are tensile, compressive, and shear strength; elastic modulus and stress-strain behavior; mechanical and thermal fatigue response; thermal expansion and thermal conductivity [12].

As it can be concluded from the literature, up to the authors’ knowledge, no studies have looked into the impact of cryogenic treatment on buckling behaviors. The buckling behavior of adhesively bonded beams has been reported in the literature, but as stated, this is not the case in a beam model formed by CFRP bonding of metal materials treated with cryogenic treatment. Determining the mechanical behavior of a bonded beam, especially the buckling behavior, is a stabilization problem, and determining beam life and critical buckling load is essential. Local deflections in the beam in advanced modes during buckling are essential for strength and adhesively bonded beam life. In this sense, this paper aims to examine the buckling behaviors of adhesively bonded beam produced cryogenically treated carbon fiber reinforced plastic (Cryo-CFRP), CFRP, steel, and aluminum. Thus, a new finite element model was adopted to estimate the buckling capacity of Cryo-CFRP composite material in the adhesively bonded beam.

3 Research Methodology

3.1 Description of the adhesively bonded beam geometry

It is known that using adhesive bonding in composite beams is more advantageous than mechanical fastening as the number of parts is reduced, and the drilling of components is eliminated. Bonded beams can be widely used for non-critical and lightly loaded structures and reliably at very high loads, often in primary aircraft structures. Also, the science and technology of adhesive-bonded joints are well understood. Pramanik et al. reviewed comprehensive knowledge regarding joining CFRP and aluminum alloys in available literature in terms of available methods, bonding processing, and mechanism and properties. The methods employed comprise adhesive to only CFRP and aluminum alloys. Besides adhesive bonding and welding, other joining methods require the penetration of metallic pins through joining parts; therefore, surface preparation is unimportant [13]. Ramaswamy et al. experimentally investigated interlocked hybrid joining technology using carbon-fiber thermoplastic composite and aluminum adherents loaded at quasi-static.

The mechanical response and damage progression were compared to baseline adhesive joints to quantify performance improvements [14]. The paper critically reviews adhesives and their various adhesion, categorization, and functions. The benefit of adhesive joining was explained. Requirements for excellent bonding, including an appropriate selection of adhesive and superior design for joining, surface cleansing, and wetting, were defined. The review clearly indicates the various theories involved in adhesion: mechanical interlocking, chemical bonding, and weak boundary layer. Bond failure modes and their mechanism were elaborated briefly [15]. Carneiro Neto et al. [16] studied the numerical evaluation of bonded joints with combined loading (traction and shear) using the finite element method, comparing the results obtained with the experiments performed at the same configurations. Considering adhesively bonded joints with the same bonded area but with different linear dimensions, the mechanical strength can be different, which characterizes the shape and adhesive type factor. Therefore, adhesives are increasingly used, and they also play an important role in joining technologies of composite beams. One of the most important advantages is that they provide uniform stress distribution, simplicity, and flexibility in manufacturing. They provide structural integrity by combining materials with different mechanical and thermal properties and are investigated using the finite element method. He [17] reviewed recent work relating to finite element analysis of adhesively bonded joints in terms of static loading analysis, environmental behaviors, fatigue loading analysis, and dynamic characteristics of the adhesively bonded joints. Accurate and reliable modeling of adhesively bonded joints is still a difficult task as the mechanical behavior of these joints is not only influenced by the geometric characteristics of the joint but also by different factors and their combinations.

It is needed to address the performance of adhesive-adherend combinations and to combine environmental and thermal studies of adhesively bonded joints. It is also essential to validate the predicted mechanical behavior of adhesive bonding structures from FEA against experimental test results. Little work in these areas has been undertaken. The output obtained from the FEA of adhesively bonded joints includes differences in the basic mechanical properties, thermal behavior, and occurrence of high-stress gradients in certain regions of the joints. Marchione [18] investigated the numerical study of the stress distribution in the adhesive layer under buckling conditions. It is possible to predict the critical load value for each single analyzed combination through numerical analysis once the critical load is determined. The results show that small adhesive thicknesses can reduce the stress peaks with the same critical load value using structural adhesives with low elastic modulus (e.g., silicones). An adhesive joint must survive longer than the estimated working life of the entire structural system. Panda et al. [19] reviewed the factors which affect the durability of an adhesive joint and the approaches to improve the durability of a joint. Thakare and Dhumne [20] reviewed the design and analysis of adhesive-bonded joint by finite element analysis regarding static loading analysis, fatigue loading analysis, and dynamic characteristics of the adhesively bonded joints. The computational analysis comprises stress and buckling analysis.

The buckling behavior of adhesively bonded structures is included in the literature, but this is not the case with a beam model formed by bonding cryogenically treated metal materials with CFRP, such as appearances. In this context, this article aims to investigate the buckling of beams by bonding cryogenically treated steel and aluminum with carbon fiber-reinforced plastic.

Fig. 1 shows the adhesively bonded beam sandwich geometry and its dimensions. The length of the beam $L = 100$ mm, the width of the beam is 10 mm, and the thickness of the one adherent panel is 1.4 mm. Adhesive thickness $b = 0.2$ mm, and the total thickness of the adhesively bonded sandwich beam $h = 3$ mm.

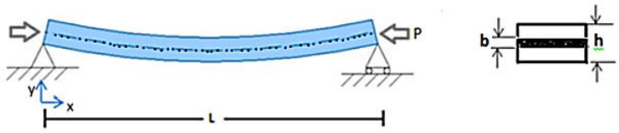

Figure 1 – Boundary conditions and dimensions for a simply supported adhesively bonded beam

Four different types of adherent material were used, and the adherent materials were chosen as Cryo-CFRP, CFRP, steel, and aluminum. One type of adhesive was used in this study. Loctite-Hysol 9464 was chosen for all adhesive bonds. The material properties of adhesive and adherent materials are shown in Tables 1-2.

Table 1 – Material properties of adhesive material [21]

Properties	Loctite-Hysol 9464
Shear Strength, MPa	22.0
Peeling Strength, MPa	10.5
Viscosity, Pa·s	270
Elastic Modulus E, GPa	1.75
Shear Modulus G, GPa	0.65
Poisson's ratio υ	0.376
Density ρ, kg/m^3	1000

Table 2 – Material properties of adherent materials [22-24]

Properties	Cryo-CFRP	CFRP	Steel St37	Aluminium 2024
Ultimate Tensile Strength, MPa	668.49	688.84	370	469
Elastic Modulus E, GPa	29.497	28.071	210	73
Poisson's ratio υ	0.1	0.1	0.3	0.33
Density ρ, kg/m^3	1600	1600	8000	2780

In this study, four different adhesively bonded sandwich beam types were modeled. First, the upper panel was chosen as CFRP material and the lower panel was chosen as steel, so a type 1 adhesively bonded sandwich beam was created. Similarly, four different adhesively bonded sandwich beam types were created, as shown in Table 3.

Table 3 – Adhesively bonded sandwich beam types

Type	Upper Panel	Lower Panel
1	CFRP	Steel, St37
2	Cryo-CFRP	Steel, St37
3	CFRP	Aluminium 2024
4	Cryo-CFRP	Aluminium 2024

The model is a supported adhesive beam subject to two opposite-edge compressions until the material buckles. The buckling behaviors of the Cryo-CFRP adhesively bonded sandwich beam and the buckling loads were studied. The elastic buckling analysis was used for the corresponding buckling shapes. The force $P = 1$ N was applied, and the response was calculated, ignoring the significant displacements effect and time-varying load.

3.2 Finite element model

The numerical model of the simply supported cryogenically treated carbon fiber reinforced plastic Cryo-CFRP (CFRP, steel, and aluminum) adhesively bonded sandwich beam patterns is developed using the ANSYS® software. The finite element program enables the prediction of buckling load and global behavior of the sandwich beam. SOLID95 is suitable for analyzing plates and adhesive layers.

The CONTA174 contact element (8-node and high order quadrilateral element) was selected to obtain the contact pairs in the finite element model. There were two contact pairs; one between the upper layer of adherent and adhesive and the other between the bottom layer of adherent and adhesive. TARGE170 was used for overlap surfaces of adherents and represented various target surfaces for the contact elements in the adhesive layer.

The Cryo-CFRP adhesively bonded sandwich beam's numerical model was divided into finite elements satisfying (3200 mesh elements) the equilibrium and compatibility at each node. Then, mesh convergence was applied. In the adhesively bonded beam, finite element analysis must be repeated to obtain the optimal convergence rate and adequate penetration by changing the defined normal penalty stiffness factor (FKN).

The contact surface is more deformable than the target surface. Therefore, the penalty method was selected as the contact algorithm. The penetration has to be as low as possible for the desired converged solution. Moreover, this is valid at high contact stiffness values. Fig. 2 shows the element types used in finite element modeling.

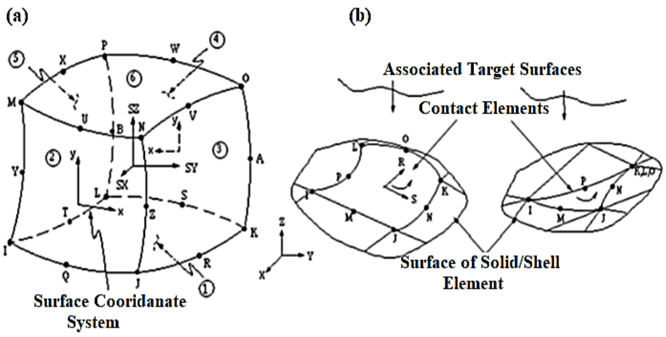

Figure 2 – Element Types: a – Solid95;
b – Conta174; c – Targe170

4 Results and Discussion

This study supported four adhesively bonded sandwich beams as simply supported. These beams were subjected to two opposite-edge compressions until the adhesively bonded beam buckled. Then the sandwich beams were numerically modeled based on finite elements.

The adhesively bonded sandwich beam structure comprised two layers and a thin adhesive layer in between. Four types of adhesively bonded sandwich beams were modeled: CFRP/Steel, Cryo-CFRP/Steel, CFRP/Aluminum, and Cryo-CFRP/Aluminum panel pairs. These panels had adhesive interlayers assumed to be linear-elastic homogeneous isotropic.

Elastic buckling analysis predicted the critical buckling load on the sandwich beams. The influences of the cryogenic treatment on the critical buckling load were presented in Fig. 3. The critical buckling loads of the sandwich beam structure panels were examined, and these loads were compared with the non-cryogenically treated CFRP sandwich structure beams. The non-cryogenically treated CFRP in the sandwich structure panels was compared to the first mode. The critical buckling load was 22.3 N for sample type 1 (CFRP/Steel). This value was determined as 3.9 N for sample type 3 (CFRP/Aluminum). As seen in Fig. 3a, the critical buckling load increased by 5.6 % when the cryogenically treated Cryo-CFRP/Steel pair was used instead of CFRP/Steel pair in the sandwich beam. This increment was calculated as 3.7 % for Cryo- CFRP/Aluminum pair was used instead of CFRP/Aluminum pair. These results presented that cryogenically treated Cryo-CFRP composite material panels responded much better against buckling.

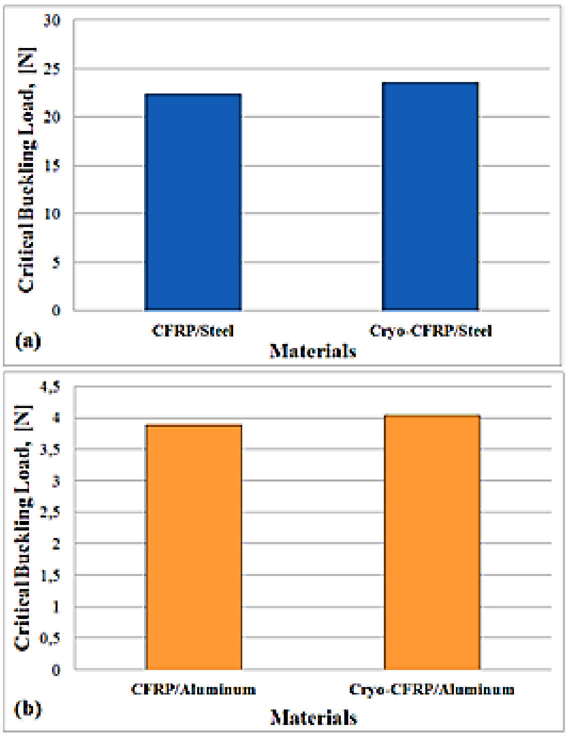

Figure 3 – Critical buckling load according to all adherent material pairs in the sandwich structure

In Fig. 4, the adherent pairs' buckling loads can be seen for each mode. Generally, the buckling load increases as the mode number increases. The buckling load increases approximately three times between mode 1 and mode 2 for the Cryo-CFRP/Steel and CFRP/Steel sandwich beam. For instance, the critical buckling load is 23.5 in mode 1, and 72.5 – in mode 2 for Cryo-CFRP/Steel sandwich beam (Fig. 4a).

As seen in Fig. 4b, when the comparison is made for the Cryo-CFRP/Aluminum sandwich beam in terms of buckling load in mode 2 and mode 1, the differences account for 198.5 %. This increment was calculated as 100.6 % between mode 3 and mode 2, and 68.8 %, 44.5 %, and 4.9 % for between mode 4 and mode 3, mode 5 and mode 4, and mode 6 and mode 5, respectively.

Also, in Table 4, the buckling loads of all samples are given for 6 modes collectively. The critical buckling loads are 3.9 N for aluminum and 22.3 N for steel in beams where CRRP bonds are formed by choosing steel and aluminum as metal materials. The cryogenically treated effect is also seen for both metal materials. Table 4 shows the critical buckling load values of 4.0 N for the Cryo-CRRP/Aluminum sample and 23.6 N for Cryo-CRRP/Steel samples. It was observed that the cryogenically treated process increased strength and positively affected buckling behavior.

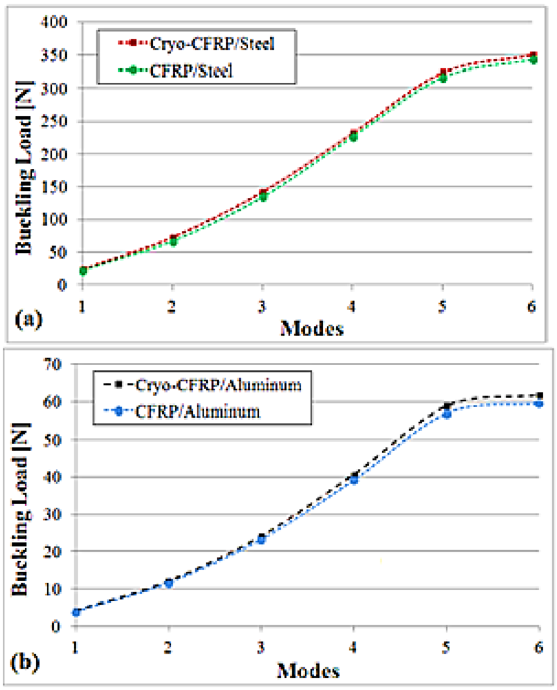

Figure 4 – Effects of the cryogenically treated CFRP material on the buckling loads for the first six modes

Table 4 – Buckling loads for six modes, N

Materials	Mode					
	1	2	3	4	5	6
CFRP/ Steel	22.3	66.8	134.4	226.5	316.9	343.2
Cryo-CFRP/ Steel	23.6	72.5	141.8	231.9	323.9	349.8
CFRP/ Aluminium	3.9	11.6	23.3	39.3	57.0	59.5
Cryo-CFRP/ Aluminium	4.0	12.0	24.1	40.7	58.8	61.7

The maximum out-of-the-plane deflection of the Cryo-CFRP/Steel adhesively bonded sandwich beam for the first six modes was presented in Fig. 5. As is known, two buckles in the adhesively bonded beam were created in mode 2. The mode shapes were similar to the other adherent materials in beams.

The deformations on *x* and *y* directions (U_x and U_y) in Cryo-CFRP/Aluminum adhesively bonded sandwich beam for six modes were given in Fig. 6-7. In the buckling analysis, the stresses are not considered, and no large deflections exist. However, there are buckles, and their locations are changed based on each mode. For mode 1, the critical buckling load is 3.9 N, and the maximum deformation on the *y* direction (U_y) is determined as 0.265 mm. For modes 2, 3, and 4, there are 2, 3, and 4 buckles, respectively. The maximum values of U_y are 0.192 mm, 0.144 mm, and 0.114 mm, respectively. However, in mode 5, the adhesively bonded beam has become stable.

Figures 5-7 show the deflections that occur because of buckling in the glued beam model for 6 modes. For mode 1 and other modes where the critical buckling load is determined, the position of both U_x and U_y directions on the beam is determined and presented by the finite element method. It is expected that a total of two buckles will occur in mode 2. At mode 5, the beam is close to the stable position.

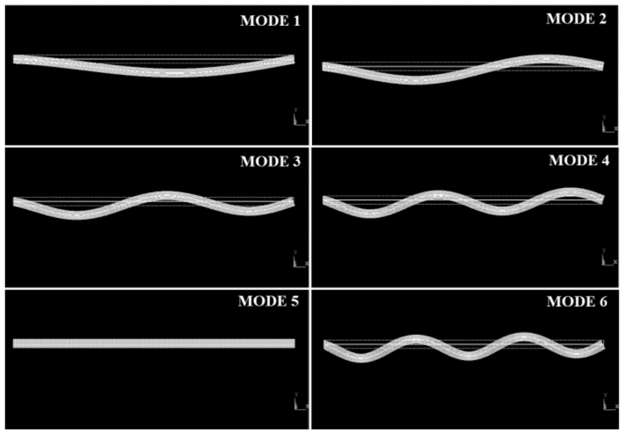

Figure 5 – Out of the plane deflections in Cryo-CFRP/Steel adhesively bonded beam for the first six modes

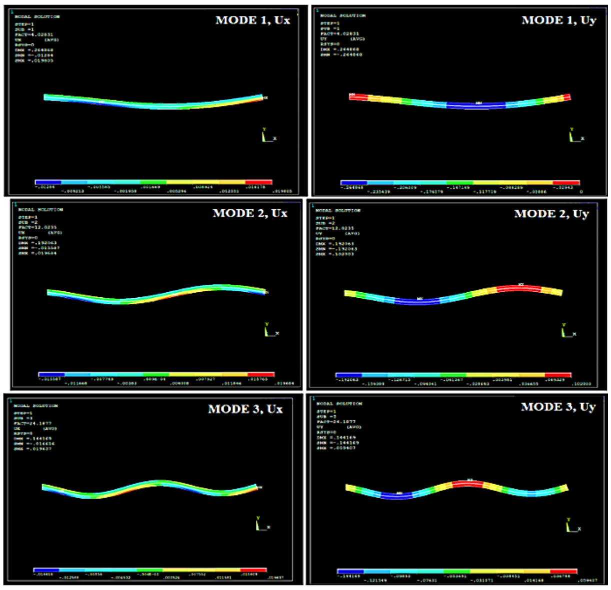

Figure 6 – The deformations on *x* and *y* directions (U_x and U_y) in Cryo-CFRP/Aluminum adhesively bonded beam for modes 1-3

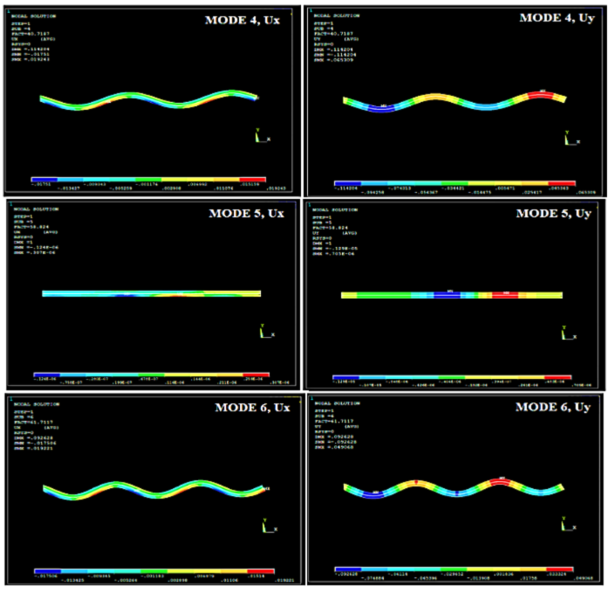

Figure 7 – The deformations on *x* and *y* directions (U_x and U_y) in Cryo-CFRP/Aluminum adhesively bonded beam for modes of 4-6

5 Conclusions

In this study, the buckling problem in the Cryo-CFRP adhesively bonded beams subjected to opposite edge compression until buckling was investigated in detail by using the developed finite element model. Four types of adhesively bonded beams were built up for buckling analysis. These models were CFRP/Steel, Cryo-CFRP/Steel, CFRP/Aluminum, and Cryo-CFRP/Aluminum.

The obtained results revealed that critical buckling was affected by cryogenically treated materials. The aluminum CFRP/Aluminum adherent selection provided the lowest critical buckling load. Critical buckling load increased by 3.7 % when using a cryogenically treated Cryo-CFRP/Aluminum couple instead of a CFRP/Aluminum couple in the sandwich beam. This increase was calculated as 5.6 % when the Cryo-CFRP/Steel couple was used instead of the CFRP/Steel couple.

The highest critical buckling load was also determined for the Cryo-CFRP/Steel among all the adherent materials. Besides, it was seen that cryogenically treated CFRP panels had the highest buckling load in all steel and aluminum beam structures when comparing the obtained results from the numerical investigation. The presented comparative results can be helpful in the buckling behavior of Cryo-CFRP adhesively bonded sandwich beams.

Nomenclature

b	Adhesive Thickness, mm;
E	Elastic Modulus, GPa;
h	Total Thickness of Adhesively Bonded Sandwich Beam, mm;
L	Length of Sandwich Beam, m;
ρ	Density, kg/m^3;
υ	Poisson's ratio;
CFRP	Carbon Fiber Reinforced Plastic;
Cryo	Cryogenic;
LN_2	Liquid Nitrogen;
U_x	Deformation on *x* direction, mm;
U_y	Deformation on *y* direction, mm.

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