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EVALUATION OF BEHAVIOR OF STITCHED EPOXY-CARBON FIBER LAMINATE UNDER STATIC BENDING CONDITIONS USING SIMPLIFIED ANALYSIS OF FAILURE ENERGY

The paper presents the attempt to assess the failure progress of a stitched carbon fiber reinforced plastic (CFRP) laminate by means of simple analysis of the failure energy after static bending tests. A laminate reinforced with a carbon twill weave (2/2) fabric, areal mass of 200 g/m^2 in the form of 10 layer preforms was used for the tests. Some of the preforms were machine-stitched with a Kevlar50 thread in lines with a 4 mm stitch length and 5 mm stitch spacing. The matrix of the composites was epoxy resin and the panels were molded by RTM. Curing took place at room temperature for three days. A fiber volume fraction of 50.5÷51.5% was obtained. Static bending tests were carried out on samples of the manufactured materials. The obtained bending curves were subjected to a simple analysis of failure energy. It consisted in determining the energy corresponding to individual stages of the material destruction progress (i.e. the areas under the bending curve) as well as direct and comparative assessment of the determined values. It was found that the applied methodology of simple analysis of the failure process energy allows effective analysis of the failure progress of materials. The total failure energy obtained by the tested laminates in the main directions is: for unstitched about 8% higher than for stitched loaded in the direction along the stitch lines and about 15% higher than for stitched loaded transversely to the stitch lines. This means that less energy is needed to destroy a stitched laminate than to destroy an unstitched one. However, a stitched laminate exhibits a higher value of failure development energy at a later stage of the failure process, which translates into its greater residual load capacity compared to the unstitched one. It was also found that the DI factor (defined as the ratio of energy used to develop the failure process to the energy used to initiate the failure process) is higher for the stitched laminate than for the unstitched one. This trend applies to all the main load directions. This means that the stitched laminate is less fragile than the unstitched one. Analysis of the obtained results indicates that the stitched CFRP laminate is a material with a safer course of destruction than a corresponding unstitched one.

Keywords: laminate, carbon fiber, static bending, failure energy

OCENA ZACHOWANIA ZSZYWANEGO LAMINATU EPOKSYDOWO-WĘGLOWEGO W WARUNKACH STATYCZNEGO ZGINANIA Z UŻYCIEM UPROSZCZONEJ ANALIZY ENERGII ZNISZCZENIA

Przedstawiono próbę oceny przebiegu zniszczenia zszywanego laminatu epoksydowo-węglowego (CFRP) za pomocą analizy energii zniszczenia, z użyciem oryginalnej metodologii prostej analizy energii zniszczenia w próbie zginania. Do badań wykorzystano laminat wzmocniony tkaniną węglową o splocie skośnym (2/2) i gramaturze 200 g/m^2, w postaci 10 warstwowych preform. Część preform przeszyto maszynowo nicią Kevlar50, jednokierunkowo, z długością ściegu 4 mm i odległością między liniami szwów 5 mm. Osnowę kompozytów stanowiła żywica epoksydowa, płyty laminatowe formowano metodą RTM. Dotwardzanie odbyło się w temperaturze pokojowej przez okres 3 dób. Uzyskano udział objętościowy włókien na poziomie 50,5÷51,5%. Na próbkach wytworzonych materiałów przeprowadzono próby statycznego zginania. Uzyskane krzywe zginania poddano prostej analizie energii zniszczenia. Polegała ona na wyznaczeniu energii odpowiadającej poszczególnym etapom postępu zniszczenia materiału (czyli pola powierzchni pod krzywą zginania) i ocenie bezpośredniej oraz porównawczej wyznaczonych wartości. Stwierdzono, że zastosowana metodyka prostej analizy energii procesu zniszczenia pozwala skutecznie analizować przebieg zniszczenia materiałów. Całkowita energia zniszczenia uzyskana w badanych laminatach, w kierunkach głównych, jest dla laminatu niezszywanego o ok. 8% większa niż dla zszywanego obciążanego w kierunku wzdłuż linii szwów i o ok. 15% większa niż dla zszywanego obciążanego poprzecznie do linii szwów. Oznacza to, że dla zniszczenia laminatu zszywanego potrzeba mniej energii niż dla zniszczenia niezszywanego. Jednakże, laminat zszywany wykazuje większą wartość energii rozwoju zniszczenia na późniejszym etapie procesu zniszczenia, co przekłada się na jego większą nośność resztkową w porównaniu z niezszywanym. Stwierdzono też, że dla laminatu zszywanego wskaźnik DI (definiowany przez stosunek energii zużytej na rozwój procesu zniszczenia do energii zużytej na zainicjowanie procesu zniszczenia) jest wyższy niż dla niezszywanego. Trend ten dotyczy wszystkich istotnych kierunków obciążania. Oznacza to, że laminat zszywany jest mniej kruchy niż odpowiedni laminat niezszywany. Analiza uzyskanych wyników wskazuje, że zszywany laminat CFRP jest materiałem o bezpieczniejszym w przebiegu zniszczenia niż odpowiadający mu laminat niezszywany.

Słowa kluczowe: laminat, włókno węglowe, zginanie statyczne, energia zniszczenia

INTRODUCTION

Evaluating the material behavior under specified loading conditions is one of the basic steps necessary to determine the applicability of this material. The main features traditionally used to determine the mechanical behavior of a material are the strength and elastic characteristics (strength, yield strength, modulus of elasticity) [1]. However, a quantity that can be analyzed as an important element in assessing the mechanical behavior of a material is the energy (work) of the material failure. Experimental analysis of the failure energy, aimed at showing a model of the course of material failure, is carried out as standard in the case of dynamic tests, where it is not easy to measure the force-displacement characteristics due to the high speed of the tests [2, 3]. It is also used in fatigue failure analyses [4, 5]. Nevertheless, energy calculations can be also used as a valuable source of information in static tests as well.

Stitching of the fibrous reinforcement of laminates is used when increased material resistance to delamination is required. At the same time, stitching adversely affects the in-plane properties of the laminate [6, 7]. The stitching of carbon reinforcements is particularly important because they are fragile materials and at the same time are often used for very responsible elements. Delamination is especially undesirable in such elements, which predisposes them to stitching. However, they are subject to great strain, which in turn intensifies the adverse effect of stitching on strength.

The paper presents two scientific aspects related to analysis of the failure energy of a material: (1) the methodology of a simplified analysis of the failure energy in a bending test, taking into account the specificity of the bending curve characteristics of an FRP laminate, (2) assessment of the course of destruction of a stitched CFRP laminate by means of analysis of the destruction energy, including an attempt to determine the effect of stitching on the progress of failure.

The motivation to take up the subject was the potential possibilities to develop the presented method and use the proposed approach in currently exploited issues such as the mechanisms and failure energy in multiphase materials containing brittle phases [8], or the influence of modification of the resin with nano-additives on its mechanical behavior as the laminate matrix (among others) creating integrated sensors that do not affect the integrity of the laminate structure [9, 10]). Research on damage energy could also significantly expand knowledge on the modification of resins with micro- and nano-additives increasing crack resistance [11, 12], modification of reinforcement structures [13] or complex structures [14, 15], including multi-material ones [16]. Energy analyses may also be of fundamental importance to verify the assessment of the failure progress of materials tested by various methods (e.g. vibroacoustic [17, 18]). Finally, calculations of the failure energy could be an interesting complement to non-destructive tests which show the damage surface and are themselves used to verify various test results [19].

The methodology presented in the paper is original, although it has similar goals as the methods used in previous works. Dynamic energy calculations for stitched glass-fiber reinforced laminates at three-point loading on Charpy's hammer were carried out in [3]. In turn, calculations of energy in the biaxial load state, with point impacts by falling mass, were done in [2]. Therefore, the work is a continuation of research into failure energy in laminates.

MATERIALS AND METHODS

The research was performed on laminates reinforced with 10 layers of carbon fabric with a twill weave (2/2) and an areal mass of 200 g/m^2. The cut pieces of fabric were stacked in preforms. Some of the preforms were machine-stitched with Kevlar50 thread in unidirectional lines along the fiber strands with a 4 mm stitch length and 5 mm stitch spacing.

The matrix of the composites was LH288 epoxy resin cured with H505 hardener (HAVEL COMPOSITES). Laminate panels were formed by the RTM method. Curing took place at room temperature for three days. A fiber volume fraction of 50.5÷51.5% was obtained in the cured composites. The unstitched laminate samples were cut from the panels in two alternative directions: along one of the main directions of the fiber arrangement (0/90, equivalent directions), and at an angle of 45° to the main directions. The stitched laminate samples were cut in three alternative directions: along the stitch lines, transverse to the stitch lines, and at an angle of 45° to the stitch lines.

The research methodology was based on conducting static bending tests of the laminate samples and subsequent analyses of the obtained bending curves. The bending tests were carried out on an INSTRON 4469 machine in accordance with the PN-EN ISO 14125 standard. The support spacing was 50 mm, travel speed 5 mm/min. An example of a bending curve is shown in Figure 1.

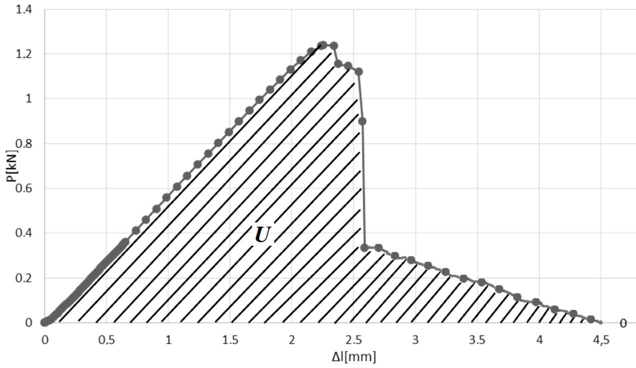

Fig. 1. Exemplary static bending curve. Hatched area represents total failure energy *U* that finally destroys the sample

Rys. 1. Przykładowa krzywa statycznego zginania. Obszar zakreskowany oznacza całkowitą energię zniszczenia próbki *U*

The theory related to the energetic foundations of the material failure process can be found in specialist literature, e.g. in [20] and [21].

The simplified analysis of failure energy, which is the subject of this work, is proposed as a method that allows one to determine and analyze the energy of individual stages of material destruction progress, without the need for specialized software or an advanced mathematical apparatus. The first step necessary to do this is to determine the size of the area under the mechanical curve, using a simple graphic method. It involves dividing the area of the curve into rectangles and adding them up. After assigning the appropriate conversion value to the rectangle surfaces, we obtain the total failure energy for a particular sample.

The total failure energy of sample U is a reliable comparative indicator for various materials. However, for analytical purposes it is necessary to divide the area under the mechanical curve into sub-areas. One of the analytical approaches already practiced in earlier studies on impact tests [2, 3] is the division into a sub-areas corresponding to the energy of the creation (initiation) of the main destruction effect in a material sample and a sub-area of developing this effect up to complete loss of material continuum in that sample's cross-section. The border of these two areas is the line running from the maximum point on the curve perpendicular to the x axis (Fig. 2).

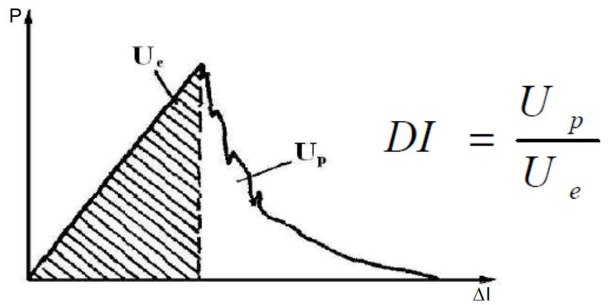

Fig. 2. Image of mechanical curve with explanation of division into area of initiation of main failure effect (U_e energy) and area of its development (U_p energy)

Rys. 2. Obraz krzywej mechanicznej z objaśnieniem podziału na obszar inicjacji zasadniczego efektu zniszczenia (energia U_e) oraz obszar jego rozwoju (energia U_p)

Determining the energy of the two sub-areas makes it possible to determine the so-called *DI* indicator (deformability index) - see Figure 2. It is a dimensionless indicator (also called viscosity index), which is probably the simplest tool to assess the brittleness of materials. It is assumed that a DI index value of 1 or less means that we are dealing with brittle material. A value above 1 means material with some deformation potential and a potential to maintain the load capacity after initiation of the main failure process.

The mechanical curves obtained for the tested laminates show some reproducible shape specificity (Fig. 3).

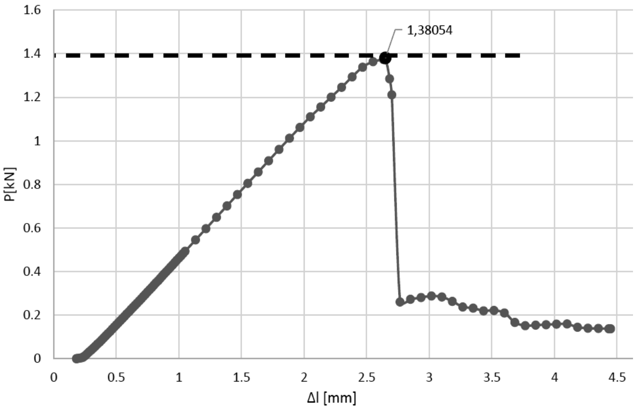

Fig. 3. Exemplary static bending curve obtained for 10-layer CFRP laminate

Rys. 3. Przykładowa krzywa zginania statycznego uzyskana dla 10-warstwowego laminatu CFRP

One problem is the lack of the end part of the bending curve - the testing machine does not bend the sample to break (unlike, for example, tensile tests). To "close" the curve, that is, to bring it to the x axis, it is necessary to add the last part of it artificially. The procedure was adopted consisting in determining two points on the final recorded section of the curve and running a straight line through which the section reaching the x axis is the final part of the curve. As the second criterion point, "b", the last point registered on the curve, was assumed. In turn, as criterion point "a", the point just before the last significant collapse of the curve was taken (significant change in derivative). Such a procedure was performed for all the curves analyzed in the paper. An example of a curve with an added end section is shown in Figure 4. For all the analyzed curves, the above described method worked well, and at the same time it can be considered simple and quite universal. It should also be emphasized that precise determination of the final section of the curve is not a matter of fundamental importance; it can at most slightly affect the error of the obtained results.

The area under the curve was divided into additional sub-areas (Fig. 4), except those shown in Figure 2. The sub-area marked C corresponds to the final stage of failure development. It is limited by the added section of the curve and ends with intersection with the x axis, which physically means a complete break in the sample continuum. Sub-area B1 represents the part of the deformation process associated with the initiation of substantial destruction. It corresponds to the fragment of the curve from the moment of its first apparent refraction (significant derivative change) to the maximum point. Subarea B2 represents the destruction development energy from the maximum point to the beginning of Area C. Dividing the area under the curve into the sub-areas described above allows a fairly reliable and complex analysis of the destruction process of a given material sample.

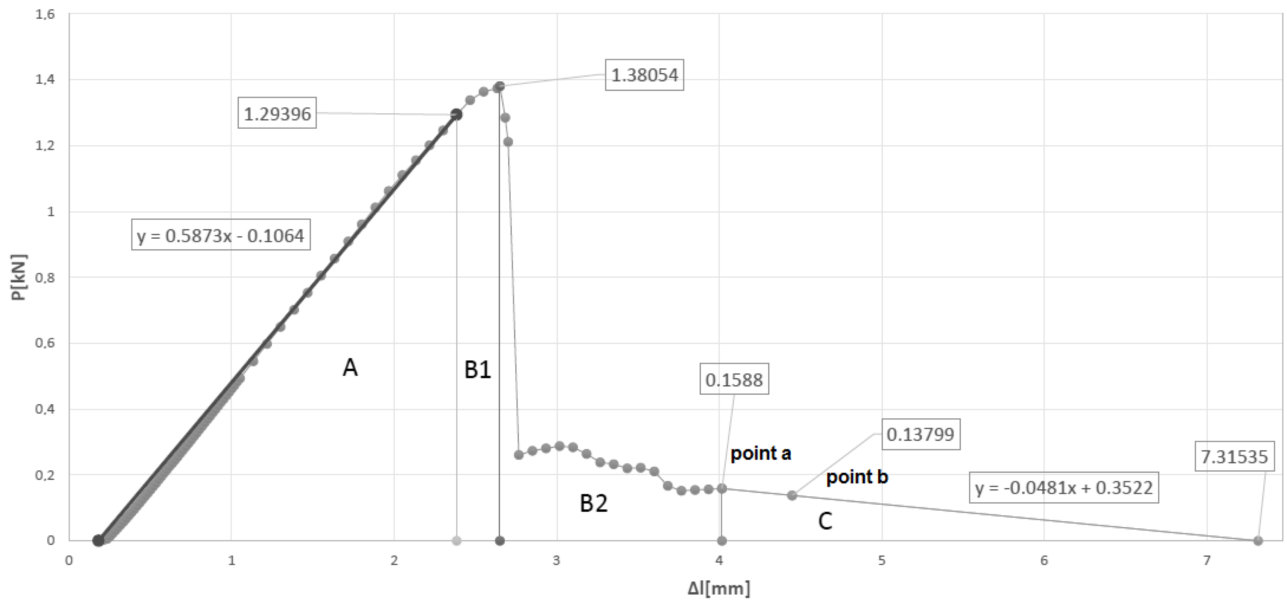

Fig. 4. Example of bending curve of 10-layer CFRP laminate with marked sub-areas (A, B1, B2, C) with added final segment being part of straight line running through point just before last significant collapse of Curve "a" and through last point on Curve "b"

Rys. 4. Przykładowa krzywa zginania 10-warstwowego laminatu CFRP z zaznaczonymi wydzielonymi podobszarami (A, B1, B2, C) wraz z pokazanym dodanym końcowym odcinkiem stanowiącym część prostej przebiegającej przez punkt tuż przed ostatnim znaczniejszym załamaniem się krzywej "a" oraz przez ostatni punkt na krzywej "b"

RESULTS ANALYSIS

The results obtained according to the procedure discussed above for the CFRP laminate will be discussed below. In some places in the text, abbreviated markings were used according to the following: 45 - laminate loaded in the direction of 45° to the fiber strands, W - stitched laminate loaded along the stitch lines, P - stitched laminate loaded transverse to the stitch lines. All the results in the form of recorded bending curves are provided in Appendix A.

Table 1 presents the energies of the sub-areas under the bending curves, for individual unstitched and stitched laminates, at various load conditions.

TABLE 1. **Average (for 4 sample series) energies of all sub-areas of bending curve for tested CFRP laminates**

TABELA 1. **Średnie (dla serii 4 próbek) energie poszczególnych podobszarów przebiegu zniszczenia dla badanych laminatów CFRP**

Laminate:	Unstitched	Unstitched 45	Stitched W	Stitched P	Stitched 45
Energy sub-area A [J]	1.19 (0.20)	0.25 (0.05)	1.21 (0.12)	0.87 (0.21)	0.54 (0.08)
Energy sub-area B1 [J]	0.43 (0.16)	2.32 (0.19)	0.23 (0.06)	0.44 (0.12)	1.41 (0.19)
Energy sub-area B2 [J]	0.35 (0.08)	1.99 (0.59)	0.66 (0.09)	0.54 (0.07)	3.06 (0.49)
Energy sub-area C [J]	0.56 (0.46)	3.73 (0.86)	0.22 (0.09)	0.31 (0.16)	3.09 (0.64)
Energy total [J]	2.53 (0.46)	8.29 (0.95)	2.33 (0.16)	2.16 (0.10)	8.09 (0.31)

Despite the fact that energy is an extensive quantity (depending on the dimensions of the system), comparing the values from Table 1 for different samples is justified because the tested samples had the same dimensions.

One can see that the total energy in the main directions is: for unstitched about 8% higher than for stitched W and about 15% higher than for stitched P. This means that less energy is needed to destroy a stitched laminate than an unstitched one. This is undoubtedly a disadvantage of stitched laminates. The highest total energy was recorded with a loading direction of 45° - it is comparable for unstitched and stitched laminates.

Unstitched and stitched laminate W exhibit similar energy in Sub-area A. This means similar energy is needed to initiate failure. However, the stitched laminate loaded in the P direction has a much lower sub-area A energy than the unstitched laminate - this is undoubtedly associated with bending on the stitch lines that create areas of reduced cross-section and stress concentration [6, 7]. This means that less energy is needed to initiate the destruction process than for an unstitched or stitched W laminate.

It is interesting that the stitched W laminate has a lower sub-area B1 value, but a greater B2 value than the unstitched. The curve in B2 is for stitched W slightly more elevated, which translates into a larger force component that creates this part of the failure energy. This also translates into greater residual strength and greater load-bearing capacity of the structure after damage - this has already been demonstrated in previous works [6, 22, 23] - especially since the stitched laminate for the P direction also has a high B2 energy level. In this direction, it also exhibits energy comparable with the unstitched B1.

Sub-area C is generally smaller for the stitched laminates than unstitched. This is due to the fact that stitching causes a more balanced failure development and the last stage (the added one), in the case of stitched laminates, on average begins at lower load values than for unstitched ones.

Table 2 presents selected relationships between individual sub-areas of failure energy.

TABLE 2. **Average DI factor and specific relations between sub-areas of bending curve for tested CFRP laminates determined on basis of average energies (Table 1)**

TABELA 2. **Średni wskaźnik DI oraz wybrane zależności między podobszarami przebiegu zniszczenia dla badanych laminatów CFRP, wyznaczone na bazie średnich energii (tab. 1)**

Laminate:	Unstitched	Unstitched 45	Stitched W	Stitched P	Stitched 45
DI factor (B2+C)/(A+B1)	0.56	2.22	0.62	0.66	3.15
B2/B1 relation	0.81	0.86	2.88	1.24	2.17
C/(A+B1+B2) relation	0.28	0.82	0.11	0.17	0.62

The DI index is the basic relationship among those determined. It previously appeared in studies [2, 3, 6]. According to Table 2, the *DI* index is generally higher for stitched laminates than unstitched ones. This difference is particularly large - an increase of nearly 50% - when loading in the direction of 45°, which is the weakest and most unsafe direction of loading a laminate with cross reinforcement. This is probably related to the milder failure progress observed earlier in the stitched laminates, where load drops are distributed over longer displacement sections compared to the unstitched laminate [6, 22]. At the same time, initiation of the failure process occurs earlier in stitched laminates (at a lower stress) than in unstitched [6, 22]. This does not change the fact that the CFRP stitched laminate is a material with a safer course of failure than the corresponding unstitched laminate.

The B2/B1 relationship shows the amount of the aforementioned B2 sub-area advantage over B1 for the stitched laminate compared to the unstitched one. It is most visible for the W direction, slightly smaller for 45° and the smallest for the P. It probably comes from the limiting effect of the stitches, delaying the progress of failure development, especially delamination [6, 24]. The residual load capacity of the stitched laminate at the stage of destruction corresponding to Sub-area B2 is higher than that of the unstitched. The bending curve of the stitched laminate is characterized at this stage by a gentle descent, instead of the rapid abrupt reduction visible in the unstitched laminate (compare the curves in Appendix A). Similar effects, even more pronounced, were observed in the case of fiberglass-reinforced laminates [6, 22].

The relationship C/(A+B1+B2) was determined mainly to assess the impact of Sub-area C, which was created as part of the work in an artificial way, on the basis of the overall assessment of the failure energy. It should be noted that it is smaller for stitched laminates than for unstitched. This means that on the last, technically irrelevant segment of the bending curve, the CFRP stitched laminate retains a lower energy percentage than the non-stitched laminate. This is approximately the same as in fiberglass reinforced laminates [6, 22]. It should be emphasized that the dependencies in Sub-areas B1 and B2 will be more important for the structural safety of the material.

CONCLUSIONS

The conducted works allow conclusions to be drawn regarding the methodology used, and the failure progress in terms of absorbed energy, in the tested stitched CFRP laminates.

The conclusion on the methodology is as follows:

1. The methodology used allows effective analysis of the failure progress of the material, taking into account the energy absorbed by the failure process. This methodology is simpler to apply and more understandable to practitioners than the methods used in scientific practice such as determining the stress intensity coefficient or energy release rate.

The conclusions regarding the failure progress in the tested stitched CFRP laminates are as follows:

2. The total failure energy obtained for the tested laminates in the main directions is: for unstitched about 8% higher than for stitched loaded in the direction of the stitch lines and about 15% higher than for the stitched loaded transversely to the stitch lines. This means that less energy is needed to destroy a stitched laminate than to destroy an unstitched one.
3. The unstitched laminate and the stitched laminate loaded in the direction of the stitch lines show similar energy needed to initiate damage. At the same time, the stitched laminate loaded transversely to the stitch lines has a much lower energy of failure initiation than in the previous two cases. The stitched laminate has a higher energy value for developing damage at a later stage of the failure process. This translates into a greater residual capacity of the stitched laminate compared to the unstitched one.
4. In general, for a carbon fiber reinforced laminate, the *DI* factor is higher for the stitched laminate than for the unstitched one. It is higher for all the relevant directions - from about 10% in the direction of loading along the stitch lines, to nearly 50% in the direction of 45°. This means that the stitched laminate is less brittle than the corresponding unstitched laminate.
5. Analysis of the obtained results indicates that the stitched CFRP laminate is a material with a safer failure progress than the corresponding unstitched laminate.

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REFERENCES

[1] Hyla I., Śleziona J., Kompozyty. Elementy mechaniki i projektowania, Wydawnictwo Politechniki Śląskiej, Gliwice 2004.

[2] Kozioł M., Evaluation of classic and 3D glass fiber reinforced polymer laminates through circular support drop weight tests, Composites Part B 2019, 168, 561-571, DOI: 10.1016/j.compositesb.2019.03.078.

[3] Kozioł M., Mechanical performance of polymer-matrix laminate reinforced with 3D fabric during three-point impact bending, Solid State Phenomena 2016, 246, 193-196.

[4] Chatys R., Investigation of the effect of distribution of the static strength on the fatigue failure of a layered composite by using the markov chain theory, Mechanics of Composite Materials 2012, 48, 6, 850-863.

[5] Paramonov Y., Chatys R., Andersons J., Kleinhofs M., Markov model of fatigue of a composite material with the Poisson process of defect initiation, Mechanics of Composite Materials 2012, 48, 2, 217-228.

[6] Kozioł M., Odporność na delaminację zszywanych laminatów polimer-włókno szklane, Rozprawa doktorska, Politechnika Śląska, Katowice 2007.

[7] Kozioł M., Nasycanie ciśnieniowo-próżniowe zszywanych oraz tkanych trójwymiarowo preform z włókna szklanego, monografia, Wydawnictwo Politechniki Śląskiej, Gliwice 2016.

[8] Oleksiak B., Kozioł M., Wieczorek J., Krupa M., Folęga P., Strength of briquettes made of Cu concentrate and carbon-bearing materials, Metalurgija 2015, 54, 1, 95-97.

[9] Szperlich P., Toron B., An ultrasonic fabrication method for epoxy resin/SbSI nanowire composites, and their application in nanosensors and nanogenerators, Polymers 2019, 11, 3, 479, DOI: 10.3390/polym11030479.

[10] Koziol M., Toron B., Szperlich P., Jesionek M., Fabrication of a piezoelectric strain sensor based on SbSI nanowires as a structural element of a FRP laminate, Composites Part B, 2019, 157, 58-65, DOI: 10.1016/j.compositesb.2018.08.105.

[11] Dydek K., Latko-Duralek P., Boczkowska A., Salacinski M., Kozera R., Carbon fiber reinforced polymers modified with thermoplastic nonwovens containing multi-walled carbon nanotubes, Composites Science and Technology 2019, 173, 110-117, DOI: 10.1016/j.compscitech.2019.02.007.

[12] Meier R., Kahraman I., Seyhan A.T., Zaremba S., Drechsler K., Evaluating vibration assisted vacuum infusion processing of hexagonal boron nitride sheet modified carbon fabric/epoxy composites in terms of interlaminar shear strength and void content, Composites Science and Technology, 2016, 128, 94-103, DOI: 10.1016/j.compscitech.2016.03.022.

[13] Dadej K., Bienias J., Surowska B., On the effect of glass and carbon fiber hybridization in fiber metal laminates: Analytical, numerical and experimental investigation, Composite Structures 2019, 220, 250-260, DOI: 10.1016/j.compstruct.2019.03.051.

[14] Bellini C., Sorrentino L., Characterization of isogrid structure in GFRP, Frattura Ed Integrita Strutturale 2018, 46, 319-331, DOI: 10.3221/IGF-ESIS.46.29.

[15] Lesiuk G., Katkowski M., Correia J., de Jesus A.M.P., Blazejewski W., Fatigue crack growth rate in CFRP reinforced constructional old steel, International Journal of Structural Integrity 2018, 9, 3, 381-395, DOI: 10.1108/IJSI-08-2017-0050.

[16] Chatys R., Kleinhofs M., Panich A., Miskow G., Composite Laminates for automotive bumpers and Lightweight Support Structures, Book Series: Engineering Mechanics 2018, 24, Eds. C. Fischer, J. Naprstek, 145-148, DOI: 10.21495/91-8-145.

[17] Figlus T., Kozioł M., Diagnosis of early-stage damage to polymer - glass fibre composites using non-contact measurement of vibration signals, Journal of Mechanical Science and Technology 2016, 30, 8, 3567-3576, DOI: 10.1007/s12206-016-0717-1.

[18] Koziol M., Figlus T., Evaluation of the failure progress in the static bending of GFRP laminates reinforced with a classic plain-woven fabric and a 3D fabric, by means of the vibrations analysis, Polymer Composites 2017, 38, 6, 1070-1085.

[19] Wronkowicz A., Dragan K., Lis K., Assessment of uncertainty in damage evaluation by ultrasonic testing of composite structures, Composite Structures 2018, 203, 71-84, DOI: 10.1016/j.compstruct.2018.06.109.

[20] Neimitz A., Mechanika pękania, Wydawnictwo Naukowe PWN, Warszawa 1998.

[21] Osipiuk W., Deformacja niesprężysta i pękanie materiałów, Politechnika Białostocka, Rozprawy Naukowe 59, 1999.

[22] Kozioł M., Śleziona J., Przebieg zniszczenia przy statycznym zginaniu laminatów poliestrowo-szklanych o wzmocnieniu zszywanym, Polimery 2008, 53, 11-12, 876-882.

[23] Kozioł M., Rutecka M., Śleziona J., Ocena wytrzymałości resztkowej zszywanych laminatów żywica poliestrowa - włókno szklane, Kompozyty 2006, 6, 2, 3-7.

[24] Mouritz A.P., Flexural properties of stitched GRP laminates, Composites Part A 1996, 27, 525-530.

Appendix A

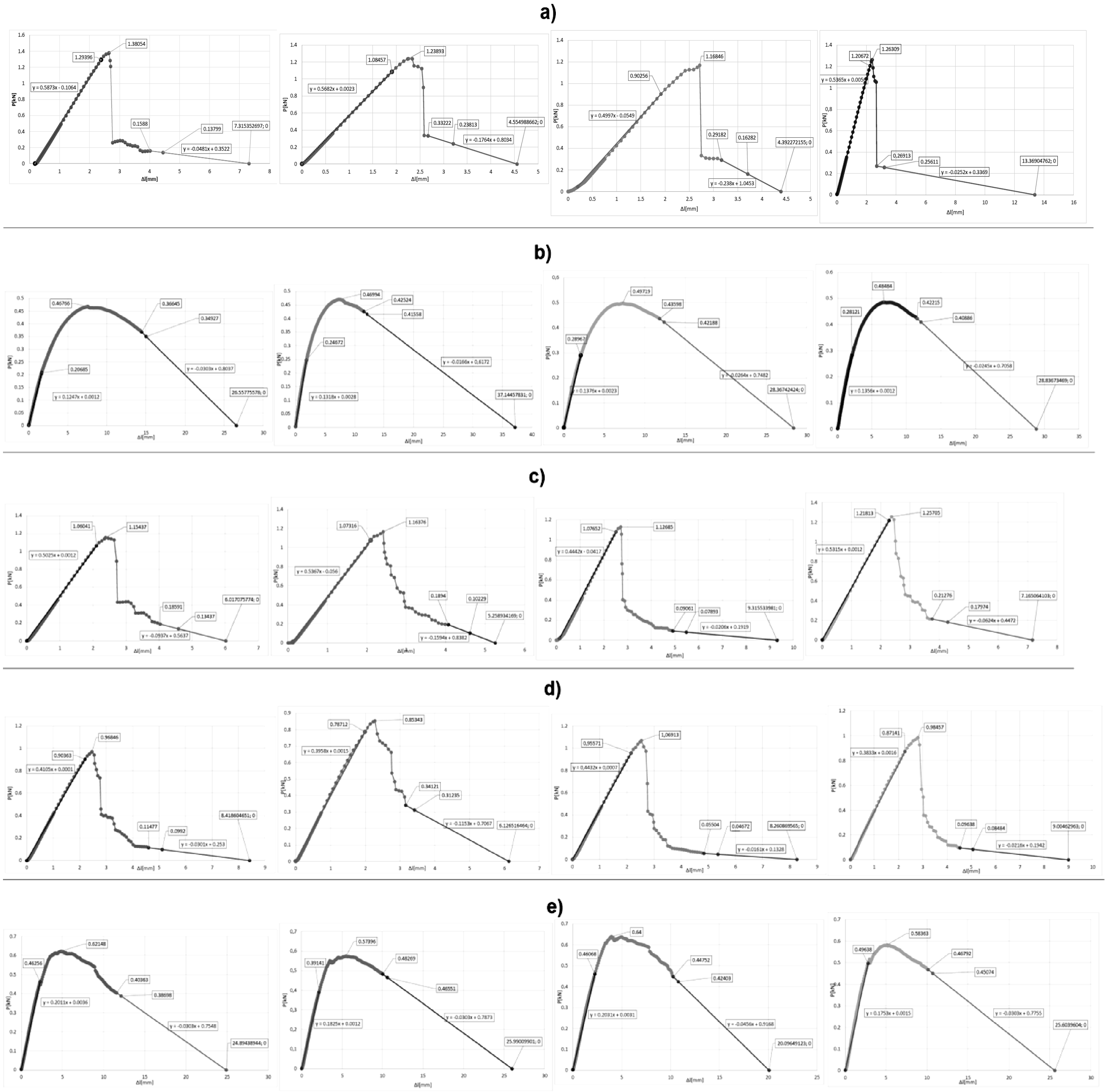

Fig. A1. Static bending curves prepared for determination of failure energy, for CFRP laminates: a) classic, b) classic, bent at 45° to the fibers, c) stitched, bent along the stitch lines, d) stitched, bent transverse to the stitch lines, e) stitched, bent at 45° to the stitch lines

