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EQUIVALENT STIFFNESS AS MEASURE OF LOW VELOCITY IMPACT DAMAGE OF COMPLEX COMPOSITE STRUCTURES

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Giangiacomo Minak[1], Snežana Ćirić Kostić[2], Zlatan Šoškić[2], Nenad Radović[1]

[1]Alma Mater Studiorum University of Bologna, Department for Industrial Engineering, Italy
[2]University of Kragujevac, Faculty of Mechanical and Civil Engineering in Kraljevo, Serbia
E-mail: soskic.z@mfkv.kg.ac.rs

Abstract. *This paper presents an analysis of the application potentials implied in the equivalent stiffness changes of complex mechanical structures as a measure of damage caused by low-velocity impacts. In a series of drop-weight tests of a commercial composite component, the impact force time variation is measured, and by calculating the respective displacement of the impacted structure, the stiffness of the structure in impacted points before and after the impacts is calculated. The determined stiffness change serves as the basis for defining a measure of damage extent that is compared to the damage extent measures based on characteristic values of the measured force. It is shown that the measure of damage based on change of stiffness has correlation with the measure of damage based on reduction of loading capacity of the structure, but it does not have correlation to the measure of damage based on ratio of maximal impact force and force needed for initial material failure.*

Key Words: *Composite Structures, Low Velocity Impacts, Damage*

1. INTRODUCTION

Composite materials are widely used in aerospace and automotive sectors both for their material properties (low density, high stiffness and strength, resistance to chemical and environmental agents), structural design potentials (ability to design material with desired anisotropic mechanical properties) and manufacturing advantages (energy saving due to low production temperatures and pressures, complicated shaped components can be molded in one process rather than being assembled from components), successfully replacing not only steel, but also light alloys in mechanical structures.

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The application of composite materials in mechanical engineering is limited by poor transverse and shear properties of unidirectional composites, which raise concern about their impact behavior. High-velocity impact behavior is relevant for safety aspects of composite structures, but low-velocity impact behavior is also of relevance for revealing their resistance to various accidental hits to which mechanical structures are exposed in regular exploitation and maintenance conditions. Such hits, some of them of repeatable nature, cause invisible internal damages which may seriously reduce loading capacity of the material.

The complete theory of impact behavior of composite materials is not developed yet due to the complex structure and versatility of composites which require studies of the problem from microscopic, mesoscopic and macroscopic points of view. Numerous research projects dedicated to the problem of the impact resistance of composite materials are performed and the published results [1-8] show that the impact behavior of composite structures in standard impact tests depends, in a complex way, on the properties of composite structures (material, thickness, laminate stacking sequence in case of laminated composites), properties of impactor (mass, velocity, energy, but also shape of impacting head) and experimental setup (clamping conditions of the test specimen).

The Impact behavior of complex composite structures represents further challenge, because of the complex influences of geometry of the structure and consequences of the particular technology applied during manufacturing of the considered structure. Therefore, the majority of research work is carried out on simple composite structures, mainly plates, in order to simplify research work, while the impact behavior research of complex composite structures is seldom published [9,10].

On the other hand, for the described reasons concerning safety and reliability, the composite structures designers need practical tools for estimation of impact resistance of the structures, even if they are not completely based on theoretical understanding of the impact processes. For this objective, various methods of estimation of damage induced by impacts are proposed.

The first group of methods aims to establish certain limiting values of impact force [11] or absorbed energy [12], which may be used for description of impact resistance of the considered structure and further estimation of impact damage. Common characteristic of these methods is that they are estimating the state of the impacted structure by characteristics that describe *the impact process*. The problem with such approach is that, in their utilization, the extent of the damage and the further behavior of the damaged composite structure cannot be determined by inspection of the structure *after* an impact. Therefore, the methods are not applicable to the practical cases of composite structures damaged during exploitation, because in vast majority of such cases the impact conditions are not known.

That disadvantage does not exist in the second group of methods, which are estimating the impact damage by *the impacted structure* characteristics. Those methods may be further divided into destructive and non-destructive ones for the impact damage characterization. The destructive methods for the impact damage characterization include CAI (compression-after-impact) tests, sectioning, thermal delamination and others, which are giving a good insight into the extent of the damage [2,14], but are of no use for estimation of the state of composite structures in exploitation. The most frequent non-destructive method for characterization of damage of impacted composite structure is measurement of size of the laminated composites delamination. The method provides a significant measure of the damage extent; yet, there is no simple and unique method for measurement of the delamination size (ultrasound C-scan, X-ray radiography, metallographic microscopy and light transmission methods are applied in various cases) [6, 15, 18], and besides, the method is applicable only to laminated composites.

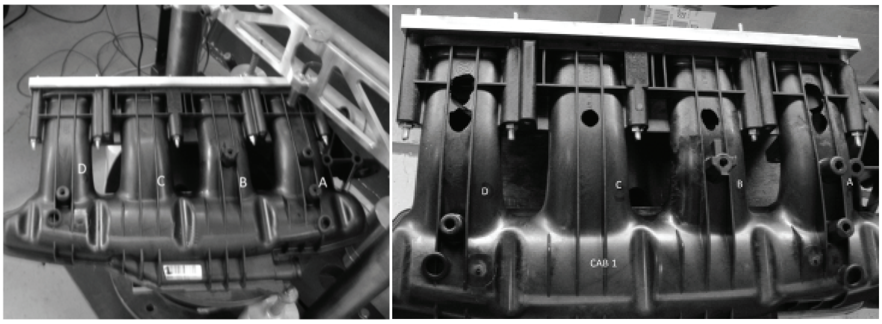

Fig. 1. Air intake manifold CAB (inlets marked by letters A, B, C and D) before (left) and after (right) series of impacts. In the upper right corner of the left picture the impactor can be seen. The holes on top parts of inlets A and D are results of further tests, not considered here.

The method for the impact damage characterization that will be analyzed in this paper is based on the well-known experimental fact that the damaged structure stiffness decreases in vicinity of the impacted point. While it is described many times and even analyzed in impact simulations, the change of stiffness is rarely used as an impact damage measure [19]. The reason for the fact is that the correlation between change in stiffness and impact damage is not easy to interpret, being that the change in stiffness may arise due to both material and structural damages induced by the impact. However, the stiffness change application should have several advantages: firstly, stiffness of the structure in any point may be successfully numerically calculated for comparison with experimentally measured stiffness of the impacted structure; secondly, measurement of the structure stiffness is comparatively easy to perform; thirdly, assuming that the damage development process in an impacted composite structure is not a stochastic but a deterministic process, the damage characterization in practice may be more important than understanding of the damage development process itself. This paper presents experimental results and initial analysis of changes of the equivalent stiffness of a commercial composite component.

2. EXPERIMENT

The experiment consists of series of drop-weight impact tests performed on commercial air-intake manifolds manufactured by Italian manufacturer "Magneti Marelli". The component (Fig. 1, in the following text just CAB) is manufactured from molding compound Ultramid, which is a composite material consisting of PA66 polyamide with reinforcement made of 35% of glass fibers. The component is manufactured by injection molding process and the glass fibers are oriented in general direction of material flow. The nominal density and tensile modulus of the material at room temperature, held during the experiment, are, respectively, $\rho = 1410$ kg/m^3 and $E = 11{,}5$ GPa, which leads to an estimation of speed of longitudinal mechanical waves in material $c = \sqrt{E/\rho} \approx 2890$ m/s. The material is characterized with comparatively very high brake strain, $\varepsilon_C \approx$ 3-5%, which, combined with the estimated speed of longitudinal mechanical waves, leads to an estimated upper limit for low-velocity impacts of $v_C = c \cdot \varepsilon_C \approx 90$ m/s.

Impact tests are performed on eight different samples of CABs, and on each of them impacts are performed at four points, located at the end of the flat part of four different inlets of the air intake manifold, denominated as A, B, C and D, as shown in Fig. 1.

The impact tests are carried out by means of a drop-weight machine equipped with an electro-optic device for measurement of initial and final velocity of the impactor, and with a piezoelectric load cell attached to the impactor for measurement of contact force variation. The impactor head is of hemispheric shape of 12.7 mm diameter. Multiple collisions are avoided by means of an electromagnetic braking system. A detailed description of the device can be found in [20]. The impactor mass is (1.22 ± 0.01) kg. Since it is already established that damage forces do not depend on impact energy [11,12], the initial height is kept constant during the experiments at level of h = 0.8 m, corresponding to a nominal potential energy change during drop of approximately 10 J. For the selected height, the free-fall impact speed is easily calculated to be $v_0 = \sqrt{2gh} \approx 3.96$ m/s, and being that the initial impact speed can be only smaller than free-fall impact speed, it is easy to conclude that the impacts in the experiment may be considered as low-velocity impacts, and treated as quasi-static mechanical processes. The CAB samples are fixed to the specially designed holder by screws, and the holder is in turn fastened to the impact rig base by clamps.

Measurement data are acquired at 100 kHz sampling frequency, without additional filtering. The reason for the absence of filtering is that, considering speeds of sound in Ultramid and steel, as well as longitudinal and lateral dimensions of impactor and CAB, it can be roughly estimated that eigenfrequencies of CAB are to be expected in the range 2.5-25 kHz, while eigenfrequencies of impactor are to be expected in the range 5-50 kHz. That estimation shows that, while a significant amount of "ringing" due to impact response of the impactor itself may be expected, it is not possible to use low-pass filters in the considered experiment for separation of response of CAB structure.

3. RESULTS

The experimental results do not reveal any significant difference between the force variations measured during impacts performed in points at inlets A, B, C and D. It appears that the influence of differences in geometry of surroundings of the points, caused by different positions of fasteners on inlets, is negligible, and that the dominant factor which influences impact resistance of the component is the thickness of the material. Therefore, for the sake of the analysis presented in this paper, all impacted points will be considered equivalent.

Experiments have shown three characteristic types of behavior of the considered CAB structures during impact tests, with typical force variations shown in Fig. 2.

The left side in Fig. 2 shows force variation during the first impact with the CAB structure at a tested point. Two sharp drops of force are visible, indicating failures of the composite materials. Both are followed by oscillations of contact force, with frequency spectra showing presence of vibrations of both impactor and the structure. Generally, the second failures do not have such a strong drop of the contact force as the one presented in the picture, but two failures are present in majority of recorded force variations recorded during the first hit of the impactor at a certain point. The duration of the impact is approximately 6 milliseconds and the maximal force measured is 1.9-2.1 kN.

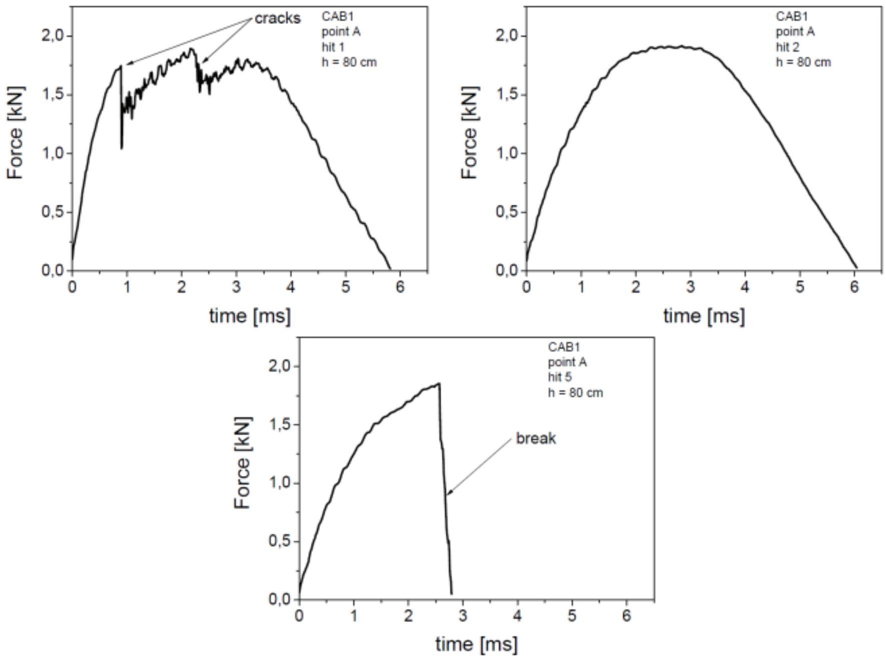

Fig. 2. Characteristic variations of the impact force recorded during experiments

The middle picture in Fig. 2 shows force variation that is characteristic for the impacts between the first and the last hit at the considered point. The impacts are characterized by approximately the same duration and maximal force as in the case of the first impact, but the force variations do not indicate any visible sign of failures, and only weak vibrations of the structure are detectable by spectral analysis of the measured force. In some cases, small drops in the contact force are present during impacts between the first and the last hit, but those failures do not change further impact behavior of the considered structure.

The right side in Fig. 2 shows force variation during the last impact with the structure at the considered point, the impact that causes penetration of impactor through the CAB structure. The impact lasts between 2 and 3 milliseconds, and the force in the moment of perforation is up to 10% smaller than maximal forces recorded during the previous impacts.

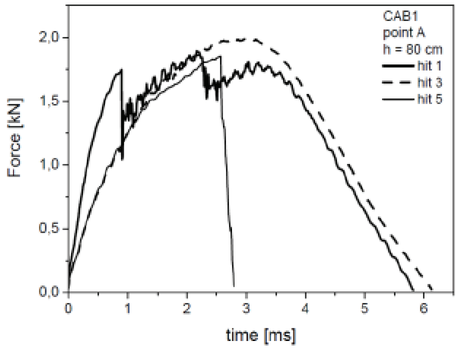

Fig. 3. Comparison of sequence of impacts at the same point of the investigated composite structure

The curves in Fig. 3 show the same variations of the impact forces as in Fig. 2, but superimposed so to make visible the change of the structure stiffness, which significantly drops after the first failure, and also decreases gradually immediately before the final structure perforation. Therefore, the stiffness changes are correlated to major failures of the considered structure, and represent an indicator of the state of the damaged structure.

Fig. 4 shows comparison between variations of the impact force recorded during the first and last impact hits to different points of the same CAB sample. Variations of the impact forces during the first impacts to different points overlap completely, indicating approximately the same initial stiffness of the structure at all considered points. However, force histories of impacts that caused perforations show that at the points where post-impact stiffness of the structure is higher, perforation forces are also higher and perforation occurred generally faster, once again indicating that the damage development process can be indicated and estimated by analyzing the investigated structure stiffness.

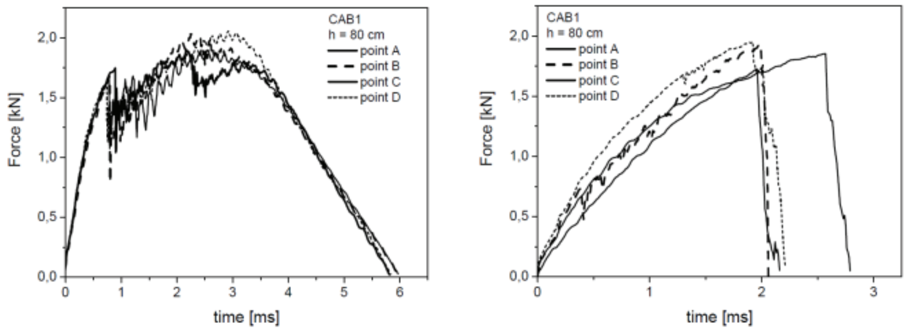

Fig. 4 Comparison of force histories of the first and last impact hits to different points of a CAB

It is, however, of importance to point out that variations of force during impacts that precede the impact with perforation do not show any sign of reduction of the structure strength, which causes structural breakdown during the impact with penetration. Further-more, even the force variation during the initial part (approximately lasting between 1 and 2 milliseconds) of the impact with penetration is the same as during the previous hits, without any precursor of incoming breakdown. Therefore, the structure stiffness changes cannot be an indicator of incoming structural breakdown.

During impact tests, impacts at 15 points caused perforation during the first impact. Therefore, while it is possible to determine the initial structure stiffness at all 32 investigated points, the change of the structural stiffness is observable only in 17 of the tested points.

4. Analysis

Structure stiffness of the impacted structure is calculated on the basis of force-displacement relation, which is determined under the following assumptions:

- the mass of the part of the impactor between piezoelectric sensor and contact point is small in comparison with the mass of the impactor, so the force acting upon piezoelectric sensor can be considered equal to the contact force between impactor and the investigated structure;
- the motion of the impactor may be considered as rectilinear, and may hence be described by an one-dimensional model;
- the displacement of the impactor and the impacted surface are equal; the difference is caused by the impacted surface indentation; due to sufficiently low impact energies used, no visible indentation is observed during the experiments, so this assumption may be considered valid;
- the impact may be considered as quasi-static process; this assumption holds when speed of the impactor is much smaller than the speed of impact wave; as discussed earlier in the section dedicated to description of impacted structure and experimental conditions, this assumption may be considered as fulfilled;
- force-displacement dependence is linear, $F \sim x$, for sufficiently small displacements of the impacted surface; it is shown earlier [21,22] that Hertzian contact law, which describes low-velocity impact with composite structures, is more complex, with loading part being described with force-displacement relation more close to $F \sim x^{1.5}$ than to a linear law; however, the assumption is still adopted because in this paper we are more interested in correlation between different measures of damage extent than to its exact mathematical form.

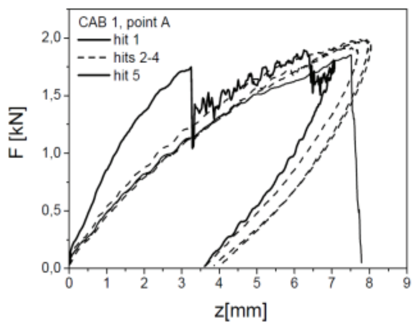

Fig. 5 Force-displacement diagram at one point CAB during subsequent impacts

If the assumptions are fulfilled, then the displacement of the impacted structure surface may be calculated by double integration of acceleration of the impactor, which is in turn calculated from the measured contact force and the known mass of the impactor. As initial time for the calculation is taken the moment of the initial contact between impactor and the impacted structure, while the upper surface of the non-deformed structure is taken as the reference level for displacement, with initial coordinate $z(0) = 0$. The initial value of the velocity, needed for the first integration, is measured by the electro-optical device that gives the actual impactor velocity immediately before impact v_0.

The form of the characteristic force-displacement relations determined for one of the impacted points is shown in Fig. 5. The figure illustrates the previously described observation that the stiffness changes due to the initial material failure and immediately before the final breakdown. It can also be noticed that during the rebound phase the contact between impactor and impacted structure is lost considerably earlier before the impacted structure returns to initial position. Considering that no indentation is observed on the impacted surface during impacts which do not cause perforation, the premature loss of the contact is attributed to strong internal friction within the composite structure.

For calculating the structure stiffness, the linear regression of initial part of force-displacement curve is used. The range to which the regression procedure is applied is determined by the algorithm that increased the upper limit of the range point-by-point until linear regression coefficient falls below the selected value.

The statistical analysis of initial stiffness calculated for all impacted points shows mean value 0.73 kN/mm and standard deviation 0.07 kN/mm, so less than 10% of the mean value. The histogram of distribution of determined values of initial stiffness is shown on the left side of Fig. 6. It shows that the determined values have normal distribution, further supporting the conclusion that all points of impacted structures should be considered equivalent.

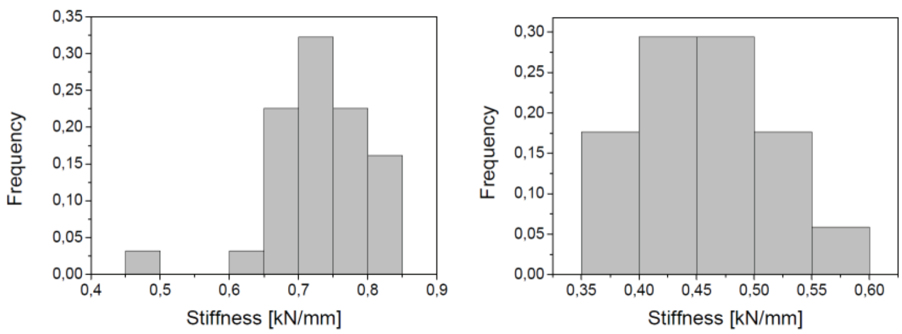

Fig. 6 Histograms of initial stiffness (left) and stiffness of the damaged structure (right)

The statistical analysis of the damaged structure stiffness, calculated for the structures which are not perforated during the first hit, reveals mean value 0.46 kN/mm, with standard deviation 0.05 kN/mm, so again around 10% of the mean value. The histogram of distribution of determined values of stiffness of damaged structures, shown at the right side of Fig. 7, suggests normal distribution of stiffness of damaged structures as well, supporting statistical approach to the problem analysis.

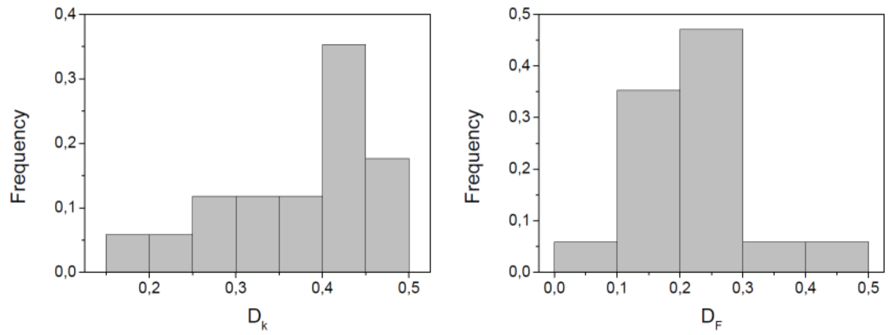

Fig. 7 Histograms of damage measured by stiffness change Dk (left) and force ratio DF (right)

The observed change of the structure stiffness may be used as a measure of extent of damage caused by impact to the investigated structure. For this purpose, we have adopted damage measure D_k defined as

$$D_k = 1 - \frac{k}{k_0}, \tag{1}$$

where k_0 represents initial stiffness of the structure, and k represents stiffness of the damaged structure. D_k is recommended in [19] as measure of damage extent, and varies between 0 (undamaged structure, $k = k_0$) and 1 (perforated structure, k=0). The histogram of distribution of damage extent, shown at left side of Fig. 7, shows rather uniform distribution of damage in range between 0.1 and 0.5, with mean value 0.37 and standard deviation 0.08.

The calculated extent of damage according to formula (1) may be compared to measure of damage extent defined in [11], which can be obtained in this type of tests, namely, measurements of force in repeated impacts with the same energy of the impactor. In [11] is suggested that a possible measure of damage extent, which characterizes residual strength of the structure, is the ratio between maximal contact force acting during impact F_{max} and force that causes initial material failure F_1. In order to scale the estimation of damage extent between 0 and 1, to make comparison easier, in this paper this measure of damage of composite structure will be defined as follows:

$$D_F = 1 - \frac{F_1}{F_{max}} \tag{2}$$

The histogram of distribution of damage extent measured by D_F, shown at the right side of Fig. 7, shows normal distribution of damage in range between 0 and 0.5, with mean value 0.21 and standard deviation 0.09. The difference in distributions of values D_F and D_k raises question about compliance of the two presented estimations of damage extent. Further comparison of estimations of damage extent measured by the two methods is shown in Fig. 8, which represents comparison between values of damage extent estimated by two methods in the same impacted points.

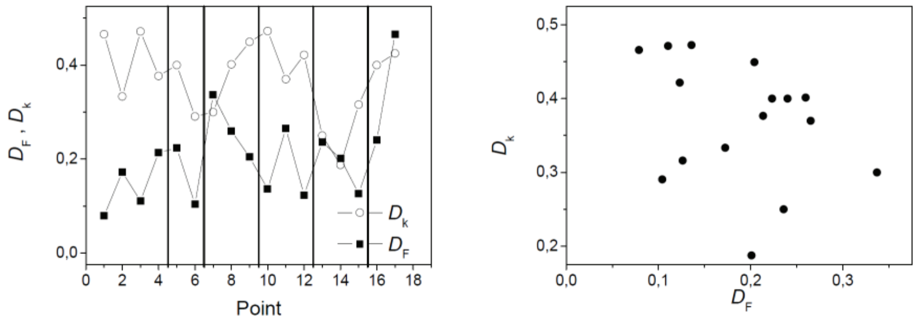

Fig. 8 Comparison of damage extents measured in different experimental points

In the graph on the left side of Fig. 8 damage extents are grouped by points belonging to the same CABs; vertical lines are separating points into groups belonging to the same CAB sample. It is visible that the trends of damage extents measured by two described measures D_F and D_k do not comply; in the first, third and fourth group of points the trends are opposite, while in the second, the fifth and the sixth group the trends are the same. That indication that damage measures D_F and D_k do not comply is further investigated by D_F-D_k diagram presented at the right side of Fig. 8, which shows that there is no correlation between the two measures of damage. Linear regression analysis shows that the probability for not having a correlation between D_F and D_k is 0.67. The described discrepancy is not clear; however, it should be stressed that [11] states that D_F "does not apply to any laminate systems whose initial damage induced by impact loading also leads to final failure". While the considered composite structure is not laminate, initial failure analyses indicated that the matrix cracking and its further growth are responsible for failure of the considered structure, which would imply that application of D_F for damage characterization might not be justified.

There is, however, another characteristic of the impact behavior of investigated structures that may be described by the measured impact forces. The damaged composite structures, as already pointed out, undergo perforation at forces with lower intensities than maximal forces that the structure is capable of bearing during previous impacts. This reduction of loading capacity may be attributed to the impact damage, and a possibility of prediction of reduction of loading capacity may be of interest for practical applications. For this purpose, a damage measure which characterizes reduced loading capacity is defined as

$$D_B = 1 - \frac{F_B}{F_{\max}} \tag{3}$$

where F_B represents force at which breakdown occurs. The histogram of distribution of D_B is shown in Fig. 9, together with repeated, for the sake of comparison, histogram of distribution of D_k.

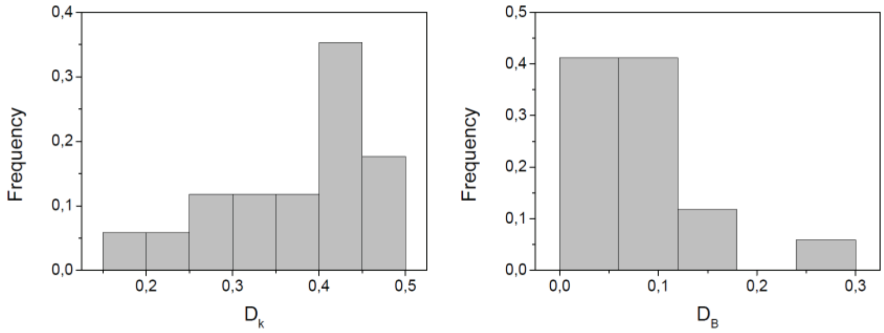

Fig. 9 Histograms of damage measured by stiffness change Dk (left) and force ratio DB (right)

It is visible that D_B has distribution of a type similar to D_k, with pronounced maximum on one flank, and a rather uniform distribution at the other flank of the distribution. Mean value of the D_B is 0.10, with large standard deviation of 0.08. More insight into correlation between D_k and D_B can be obtained by diagrams presented in Fig. 10, which, analogous to the ones presented in Fig. 8, represent comparison between values of damage extent estimated for the same impacted points.

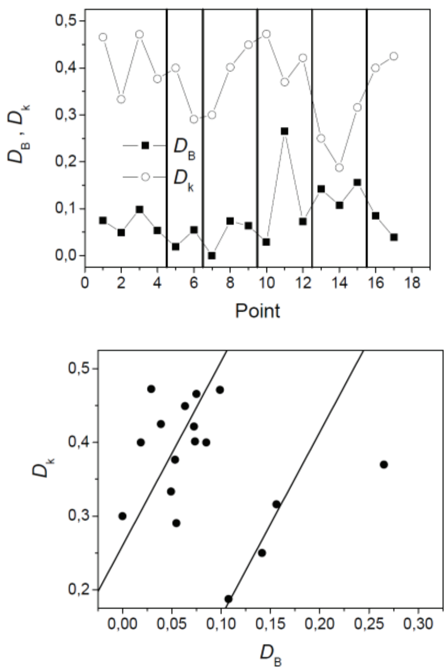

Fig. 10 Comparison of damage extents measured in different experimental points

While separation into groups does not indicate more compliance between the trends predicted by two damage measures (the first, the third and the fifth group show the same trends, while the second, the fourth and the sixth group show opposite trends of D_K and D_B), the D_K–D_B diagram reveals that there is a significant correlation between the measures of damage. The correlation is further enhanced when points with particularly high values of D_B are separated for the sake of analysis. It turns out that three of these four highest values describe points on the same CAB, which is, for unknown reasons, exceptionally sensitive to impacts. After separation of the points in two groups, as shown in the diagram on the right side of Fig. 11, it turns out that both groups have similar linear regression coefficients close to 2.5, with correlation coefficient of the larger group $R \approx 0{,}44$ and probability of non-correlation around $p \approx 0{,}135$, suggesting the existence of correlation between D_B and D_k.

5. Conclusion

This paper gives an approach to description of impact damage of complex composite structures by changing the structure stiffness at impact points.

The analysis is based on experimental testing of series of commercial composite air-intake manifolds which are exposed to repeated low-velocity impacts on drop-weight impact rig. The experiments assumed that the time variations of the contact force during impacts are recorded. The acquired data further serve for calculating displacements of the impacted structure and on the basis of thus established force-displacement relationships the structure stiffness values at the impact points are calculated. The values of stiffness show that the stiffness of the damaged structures is reduced.

On the basis of the change of stiffness, by means of equation (1), the damage extent is introduced as a measure. The measure is compared to that described by equation (2), previously proposed [11] for laminated composites, that is based on ratio between the force which causes initial failure of the structure and the maximal force acting during an impact. The obtained results show that there is no correlation between the two measures of damage. Besides, an additional measure of damage is introduced by equation (3), which is based on reduction of loading capacity of damaged composite structure during subsequent impacts. The statistical analysis shows that a significant correlation exists between the estimation of damage based on change of stiffness of the structure and the estimation of damage based on reduction of loading capacity of damaged composite structure.

The results of the analysis presented in this paper encourage further research of applicability of change of stiffness as measure of damage arising in composite structures as a consequence of low-velocity impacts. Considering that the structural stiffness measurements may be performed easier than other non-destructive tests and that structural stiffness can be successfully numerically calculated, the application of stiffness change as measure of damage extent could be a useful practical tool for estimating the damage of composite structures.

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EKVIVALENTNA KRUTOST KAO MERA OŠTEĆENJA SLOŽENIH KOMPOZITNIH STRUKTURA PRI UDARIMA MALIM BRZINAMA

Giangiacomo Minak, Snežana Ćirić Kostić, Zlatan Šoškić, Nenad Radović

Rad predstavlja analizu mogućnosti primene ekvivalentne krutosti složenih mehaničkih struktura kao mere oštećenja prouzrokovanih udarima malih brzina. U serijama testova kontrolisanih udara u komercijalnu komponentu načinjenu od kompozitnog materijala merena je promena udarne sile tokom udara, a daljim proračunom deformacije udarane komponente je izračunata njena ekvivalentna krutost u udaranim tačkama pre i posle udara. Na osnovu utvrđene promene krutosti definisana je mera oštećenja koja je upoređena sa merama oštećenja zasnovanim na karakterističnim vrednostima izmerene udarne sile. Pokazano je da mera oštećenja zasnovana na promeni krutosti ima korelaciju sa merom oštećenja zasnovanoj na smanjenju nosivosti strukture, ali da nema korelaciju sa merom oštećenja zasnovanoj na odnosu maksimalne udarne sile i sile pri kojoj nastaje početno oštećenje komponente.

Ključne reči: *kompozitni materijali, mašinske konstrukcije, udari malim brzinama, oštećenja*