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COMPOSITES THEORY AND PRACTICE

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ISSUES RELATED TO DETERMINING EFFECTIVE ULTIMATE STRENGTH, MAKING PROVISION FOR UNDETECTABLE DAMAGE

A simplified procedure for determining effective ultimate stress that could account for the adverse effects of undetected damage done to laminates was described. The procedure was based on the assumptions that an equivalent open hole (EOH) existed that could appropriately represent the extent of damage for the purpose of calculating strength and that the laminate under consideration was notch sensitive. Particular emphasis was placed on the assessment of BVID extent, which was crucial to define the EOH dimensions. The results of different inspection methods concerning the damage extent were presented and compared with each other. Moreover, it was experimentally shown that for a typical inspection condition the detectability threshold of BVID expressed in terms of indentation depth, δ, and was 262 μm. It was found that the extent of damage defined based on visual inspection was significantly different from that defined based on C-scans and fractographic inspections. It was concluded that to determine the EOH dimensions, the damage measurements were not sufficient while definition of the EOH dimensions could be based on the equal values of the stress concentration factor caused by the damage of a given extent and EOH.

Keywords: BVID, equivalent hole, detectability

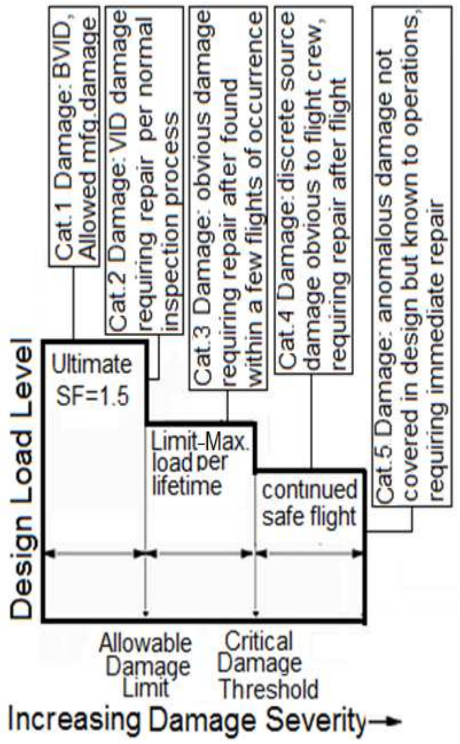
ZAGADNIENIA ZWIĄZANE Z WYZNACZENIEM ZASTĘPCZEJ WYTRZYMAŁOŚCI DORAŹNEJ LAMINATU, UWZGLĘDNIAJĄCEJ OBECNOŚĆ NIEWYKRYWALNEGO USZKODZENIA

Jedną z istotnych danych materiałowych koniecznych do przeprowadzenia obliczeń wytrzymałościowych jest wytrzymałość doraźna. W praktyce badany materiał zawsze zawiera wady lub uszkodzenia i tylko sprawą doskonałości metod inspekcji jest to, czy zostaną wykryte czy nie. Zagadnienie to jest istotne w odniesieniu do kompozytowych struktur lotniczych podlegających, między innymi, uderzeniom niskoenergetycznym. W ich wyniku pojawiają się prawie niedostrzegalne uszkodzenia, trudno wykrywalne na drodze inspekcji wizualnej stanowiącej typową metodę postępowania w trakcie przeglądów bieżących. Jak wykazały laboratoryjne metody inspekcji, uszkodzenia takie mimo niewykrywalności metodami wizualnymi powodują znaczące uszkodzenia wewnętrzne struktury. W artykule zaproponowano wprowadzenie pojęcia efektywnej wytrzymałości doraźnej oraz procedurę jej wyznaczania. Wartość efektywnej wytrzymałości doraźnej uwzględniałaby deprecjonujące oddziaływanie takich, wykrywalnych z małą dozą prawdopodobieństwa uszkodzeń. Istotnym elementem zaproponowanej procedury jest wyznaczenie granicy wykrywalności uszkodzenia oraz sposobu ustalenia rozmiarów otworu ekwiwalentnego, kołowego lub eliptycznego, co ułatwiałoby analizy wytrzymałościowe. W artykule przedstawiono sposób określania rozmiarów uszkodzenia o granicznej wykrywalności, tj. wykrywalnych nie mniej niż w 90% przypadków. Stwierdzono, iż w wyniku rutynowej inspekcji okresowej płatowca, dokonywanej w typowych warunkach, jedynie przy pomocy nieuzbrojonego oka, rozmiarem granicznym trudno dostrzegalnych uszkodzeń udarowych jest wgniecenie o głębokości nie mniejszej niż 262 μm. Przyjęto, iż otwór ekwiwalentny będzie otworem, którego obrys zewnętrzny należy opisać na odnośnym uszkodzeniu, jednakże jak wykazały dokładniejsze metody inspekcji, rozmiar uszkodzenia może być różnie definiowany, zależnie od czułości metody inspekcji. Porównanie rozmiarów konturu wgniecenia widocznego na powierzchni z rozmiarami wewnętrznego uszkodzenia zdefiniowanego na podstawie C-skanów lub zgładów wykazało, iż rozmiary odcisków są, w przybliżeniu, o rząd mniejsze od rozmiarów uszkodzeń wewnętrznych. Jednakże, uszkodzenia wewnętrzne w przeważającej mierze to delaminacje i pęknięcia wewnątrzwarstwowe spoiwa i nie skutkują całkowitą redukcją sztywności materiału. Stąd można wnioskować, iż zdefiniowanie rozmiarów otworu ekwiwalentnego wymaga bardziej precyzyjnego kryterium, np. kryterium jednakowego współczynnika koncentracji naprężeń. Zaproponowano, iż otworem ekwiwalentnym może być np. otwór o rozmiarze *r*, który powoduje spadek nośności elementu próbnego o zadanym stosunku *r*/*w* taki, jaki spowoduje rozpatrywane uszkodzenie o rozmiarze *a*, zaistniałe w elemencie próbnym o takiej samej szerokości (przy czym uprzednio należy uściślić definicje rozmiaru *a* uszkodzenia). Testy powinny obejmować elementy próbne o różnej wartości *r*/*w* i *a*/*w*, by sprawdzić, czy oczekiwana zależność obowiązuje w wymaganym zakresie ich wartości.

Słowa kluczowe: BVID, ekwiwalentny otwór, wykrywalność

INTRODUCTION

The tolerance of polymer composite air frames to Barely Visible Impact Damage (BVID) is a complex problem. BVID is in the Category 1 damage bracket [1], Figure 1.



Rys. 1. Regulatory airworthiness requirements relating damage or defect size to load capacity of structure. Precise definition of damage categories can be found in [1]

Fig. 1. Wymagania przepisów zdatności do lotu w odniesieniu do relacji między rozmiarami uszkodzenia/wady i nośności zawierającej ją struktury. Precyzyjna definicja kategorii wskazanych uszkodzeń może być znaleziona w [1]

Category 1 damage includes allowable damage that may go undetected by scheduled or directed field inspection or allowable manufacturing defects. Some examples of this category damage include BVID and allowable defects arising during manufacturing or service (e.g., small delaminations, porosity, small scratches, gouges, and minor environmental damage). Specific problems associated with such defects consist in the fact that they often remain undetected, however, they can affect the load capacity of the structure. Furthermore, the threat to the structural integrity they produce is difficult to assess by means of stress analysis since the defects or damage cannot be defined in terms of geometry and location due to the aforementioned reasons. In the body of this paper a particular procedure is suggested that could help to tackle the above mentioned problems. The procedure aims to determine such a far field stress that could be assumed as an ultimate one making provision for undetected damage in the laminate structure under consideration.

PROPOSED PROCEDURE

The proposed procedure has been designed for implementation in a certification process of a certain composite airframe to simplify it. This procedure can be considered as a part of a more general certification process. It takes into consideration the Airworthiness Requirements which define the relationship between the damage size and the required corresponding residual load capability of an airframe structure for Category 1 damage.

The procedure is illustrated by a block diagram (Fig. 2). The main problem in its implementation consists in determining the relationship between the BVID extent and the dimension of the Equivalent Open Hole (EOH). A hole that can be assumed to be an EOH must produce the same Stress Concentration Factor (SCF) for a varying plate width as the damage it represents does. If such an EOH can be set for undetectable damage, it can be used to determine the effective ultimate stress (EUS) taking into account such damage.

Step 1. Determination of damage geometry: dent depth,δ, and in-plane dimensions	Step 2. Determination of EOH	Step 3. Determination of effective ultimate strength associated with EOH under consideration

Rys. 2. General algorithm of simplified procedure to determine ultimate strength that makes provision for adverse effect of BVID

Fig. 2. Ogólny algorytm uproszczonej procedury wyznaczania wytrzymałości doraźnej uwzględniającej istnienie trudno wykrywalnych uszkodzeń udarowych

It is claimed in [2] that for quasi-isotropic laminates, an in-plane geometry of impact induced damage can be well represented by an ellipse circumscribing the damaged area, however, a definition of the damage extent and the way it can be defined were not given. It will be shown in the following section that the problem is not trivial. The simplest way to determine the EOH geometry would be to take measurements of a visible indentation at the detectability threshold. A more elaborate method is presented in [3]. In the case of far field compression, this method recommends calculating a minor ellipse axis 2b parallel to the loading direction according to:

$$b = \sqrt{2r\delta - \delta^2} \qquad (1)$$

where r is the radius of the impactor hemisphere and δ is the indentation depth.

Once the dimensions of the EOH are established, the remote failure stress can be determined experimentally based on the strength of a finite width specimen, w, containing the EOH of an assumed radius, r, (or a and b dimensions in the case of an ellipse). Assuming that the Correction Factor (CF) is known, this result can be used for a specimen of any r/w ratio with the help of (2), since in a quasi-isotropic laminate, $SCF_\infty = 3$ for a circular hole and for an ellipse can be calculated with the help of (3) [3, 4]. In the case of other laminates, its value varies depending on the reinforcement arrangement and loading direction [5, 6].

$$SCF_{fw} = SCF_{\infty}\, CF \qquad (2)$$

where SCF_{fw} and SCF_{∞} are the stress concentration factors for holes in specimens of finite and infinite widths, respectively:

$$SCF_{\infty} = \frac{\sigma_N}{\sigma_{\infty}} = \left(1 + 2\frac{a}{b}\right) \qquad (3)$$

where: σ_{∞} - remote stress, σ_N - circumferential stress at the hole edge for $\theta = 90°$ relative to the loading direction a and b - halves of major and minor ellipse axes, respectively (see Fig. 4).

For elliptical and circular holes the CF is given by:

$$CF = \frac{2 + \sqrt[3]{1 - \frac{2a}{w}}}{3\left(1 - \frac{2a}{w}\right)} \qquad (4)$$

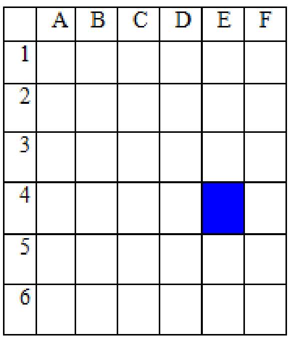
where: w - the specimen width and a is a half of the ellipse axis perpendicular to the loading direction or the radius of a circular hole.

To establish the EOH, the following strategy could be applied. The strength and SCF for several specimens of different widths containing BVID of the same extent, (as close as possible), can be determined at the same time. Then the results obtained with the help of (2), (3) and (4) for specimens of varying hole size over a specimen width ratio e.g. r/w, can be compared against the experimental ones and the choice of EOH size can be made based on the best match of the results.

Remote failure stress calculated with the help of the EOH corresponding to the damage extent of the indentations just below or just above the established detectability threshold, (for the assumed inspection method), can be taken as the EUS that makes provision for an adverse effect of damage undetectable by the assumed inspection method.

BVID DETECTABILITY

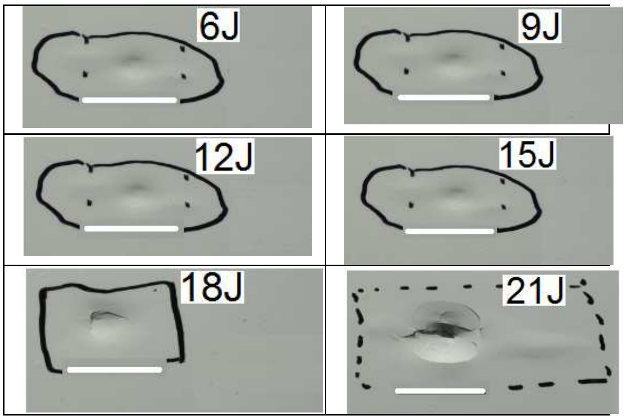
1. Below, the following issues related to the aforementioned procedure are addressed, i.e.: BVID detectability
2. Assessment of BVID extent



Rys. 3. Array of 36 tiles. Location of damaged tile (in blue) was changed for each trial

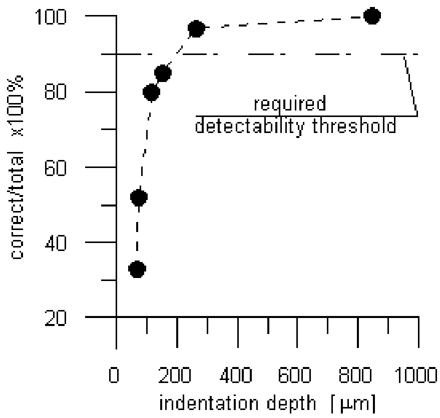
Fig. 3. Trzydziestosześciopłytkowa plansza. Pozycja płytki z uszkodzeniem (w kolorze niebieskim) była zmieniana w trakcie przeprowadzania prób

Thirty six nominally identical 100 x 150 mm laminate tiles were put together to form an array (Fig. 3). The tiles were made with 20 layers of CF/epoxy Vacuum Bag Only (VBO) prepreg with $[0/90/0/90/0/0/45/\text{-}45/\text{-}45/45]_S$ reinforcement orientation. The tiles were vacuum bag cured for 4 h at 130°C.



Rys. 4. Impact imprints shown to inspectors. Length of white line section corresponds to 2 mm

Fig. 4. Wgniecenia w płytkach pokazanych inspektorowi. Długość białego odcinaka odpowiada 2 mm



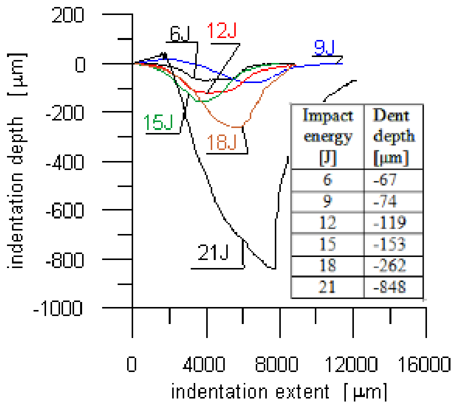
Rys. 5. Damage detectability in terms of correct over total answers ratio versus indentation depth. Required detectability threshold of 90% is acceptable by aviation authorities

Fig. 5. Wykrywalność uszkodzeń udarowych wyrażona w procentach prawidłowych odpowiedzi w stosunku do wszystkich odpowiedzi. Wymagana przepisami wykrywalność powinna wynosić co najmniej 90%

The location of the damaged tile amongst the other tiles forming the array was only known to the person conducting the test. The damaged tiles contained BVIDs produced by the impactor hitting the tile with the prescribed energy. The impactor had on its end a hemisphere of r = 12.7 mm. The tile array was inspected by a group of 10 untrained people asked to indicate the damaged tile by naming the appropriate row and column numbers (Fig. 3). The sample was repeated six times and each time the damaged tile was relocated to make its position unknown to the investigators. Such a procedure was repeated six times for each of 6, 9, 12, 15 and 21 J impacts. The visual inspection conditions were as follows: Each person was allowed

5 s for inspection carried out from a 1.5 m distance. The inspected surface was painted white, washed and illuminated with white light of a luminance of 450÷550 lux. Pictures of the imprints produced by impacts of prearranged energy values are shown in Figure 4. The results in terms of the correct over total answers ratio expressed in percent of the total number versus indentation depth are shown in Figure 5.

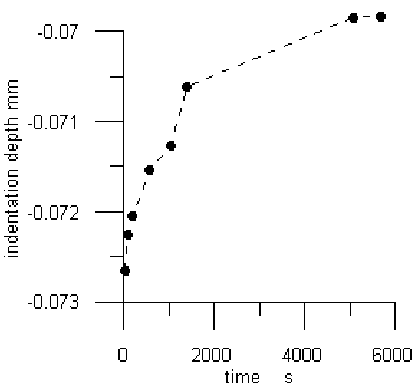
Several methods of nondestructive testing (NDT) could be used for damage inspection of composite air frames [8, 9]. The accuracy of these methods determines the BVID detectability threshold. For the economic and practical reasons previously presented, a simple visual inspection method prevails in the case of scheduled or field airframe inspection [1]. Therefore, it was assumed that the sensitivity of this method defines the detectability threshold of BVID for the purpose of the proposed procedure.



Rys. 6. Indentation depths and profiles

Fig. 6. Głębokości i profile wgnieceń

It was expected that the depths of the indentation would decrease with time due to the viscosity of the material and for this reason the initial indentation depths and profiles (Fig. 6), were determined with the help of a digital microscope. To assess these changes, the indentation depths were measured at certain time intervals. An example of such indentation measurements is shown in Figure 7.



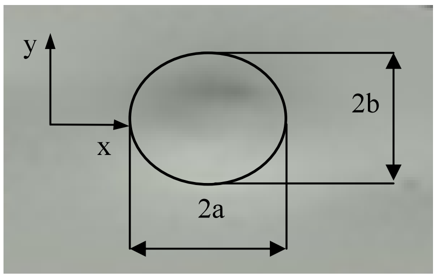
Rys. 7. Variation of dent depth with time for dent resulting from 9 J impact

Fig. 7. Zmiana w czasie głębokości wgniecenia spowodowanego uderzeniem o energii 9 J

The plot represents changes in the indentation depth produced by a 9 J impact. A decrease in depth after 5000 s was about 3.5% of the initial value and, practically, after this period of time the indentation depth remained constant. The measurement uncertainty of the equipment did not exceed ±2 µm according to the information provided by the manufacturer. For other indentations, the results were similar and for further considerations the depth changes were considered negligible.

ASSESSMENT OF INTERNAL DAMAGE EXTENT

Unfortunately, the visual method has a significant drawback consisting in the fact that it does not provide sufficient information about through-thickness damage which is crucial for determining the EUS. To gain this information, additional tests were carried out with the help of the ultrasonic puls-echo method that provided C-scans of the damages. After these tests the specimens were sectioned along the longer axis of the ellipse and fractography examination was performed. All the results were compared against each other. To facilitate the comparison, when possible, the damage was defined in terms of the axes of the ellipse encompassing the damage (see Fig. 8 for an example dent).



Rys. 8. Described ellipse of impact imprint. Usually for quasi isotropic laminate a≈b≈R [3]

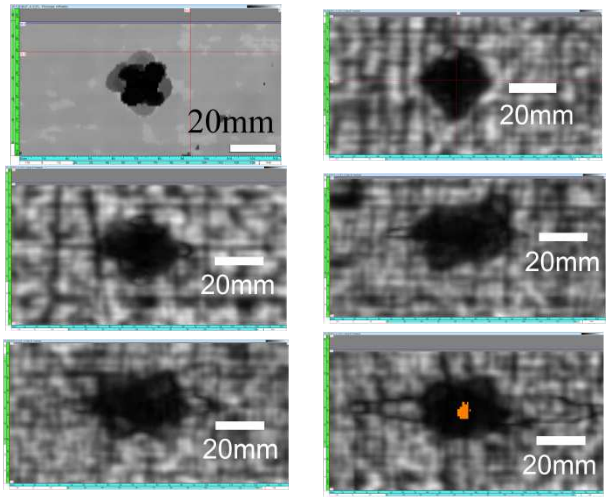
Fig. 8. Elipsa opisana na wgnieceniu spowodowanym uderzeniem. Zwykle w przypadku laminatu quasi-izotropowego a≈b≈R [3]

The results of the ultrasonic and fractographic inspections are shown in Figures 9 and 10 and collation of all the results is given in Table 1.

TABLE 1. **Length of ellipse axes [mm]**
TABELA 1. **Długość osi elipsy [mm]**

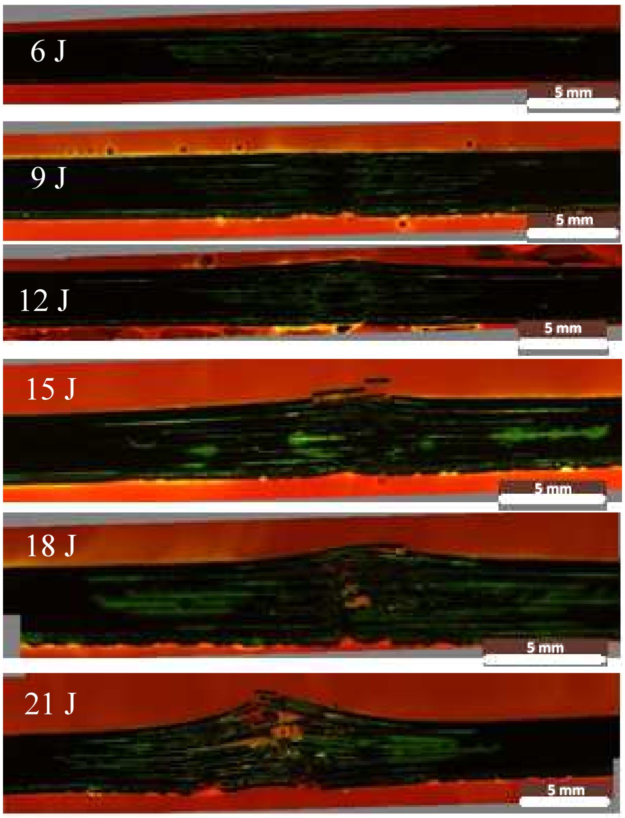
Impact energy [J]	Inspection method				
	visual [mm]		fractography [mm]		C - scan [mm]
	a	b	a	b	a
6	-	-	25.8		27
9	-	-	30.8		31
12	3.1	2.3		29.8	43
15	3.8	2.6		23.5	47
18	5.2	4.1		22.3	42
21	9.7	9.3		23.0	37

The cells with a gray background contain the results for damage above the established detectable threshold of visual inspection.



Rys. 9. C-scans of impact damage areas

Fig. 9. C-skany obszaru uszkodzeń



Rys. 10. Fractography of impact damages. Sectioning along major ellipse axis. Length of white line section corresponds to 5 mm

Fig. 10. Zgłady ukazujące zasięg zniszczenia wewnątrz laminatu. Przekroje zostały wykonane wzdłuż dłuższej osi elipsy opisanej na widocznym wgnieceniu. Długość białego odcinaka odpowiada 5 mm

DISCUSSION OF EXPERIMENTAL RESULTS

The C-scans indicated that in each case the extent of internal damage was several times larger than that indicated by the corresponding imprints. Of particular interest were the extents of internal damage corresponding to the imprints considered to be just below and just above the established detectability threshold, i.e. of indentation depths equal to 153 μm and 262 μm, respectively. It was found that the internal damage extents were similar in both cases. Based on visual inspection, their in-plane dimensions (imprints) were a = 3.8 mm and b = 2.6 mm, for the 153 μm indentation and a = 5.2 and b = 4.1 mm for the 262 μm indentation while the C-scans results yielded a = 47 mm and b = 33 mm, and a = 42 mm and b = 28 mm respectively. Furthermore, the C-scan results revealed that for all the cases the internal damage extents were similar.

In general, assessment of the damage extents done with the help of C-scans and fractographic examinations indicated that the measurements of impact imprint yielded severe underestimation of the internal laminate damage. While the fractography and C-scan based measurement results were close to each other, they differed by one magnitude in favor of C-scans. However, comparison of the fractographic inspection results that could be considered as the most credible against that of ultrasonic ones, indicated that the former overestimated the damage. The application of formula (1) for calculating the damage geometry turned out to be misleading since it suggested a large difference in lengths between the ellipse axes which was confirmed neither by the imprints nor by the C-scans.

SUMMARY AND CONCLUSION

The simplified procedure for determining far field stress that could be taken for an EUS accounting for the adverse effects of a non-detectable BVID was proposed. To apply the procedure one must select an inspection method and determine its detectability threshold. In this case visual inspection was assumed and its detectability threshold was determined in conditions similar to that of field inspections. The findings were compared against the results provided by C-scans and fractography inspections. A large discrepancy between the visual and internal damage extents was revealed for each energy impact.

Depending on the criteria assumed, i.e. the size of the imprints or internal damage extents exposed by fractography or by C-scans, the diameters of equivalent holes could vary by more than one magnitude, e.g. for a 15 J impact it could be 3.8 or 47 mm. Assuming that the EOH should encompass the damage, it could be concluded that the size and way the size of the EOH should be determined are not obvious. To solve this problem, additional extensive testing would be required and it would consist in:

- Establishing stress concentrations for plates of varying width, w, containing BVID of the same extent let us say, a, i.e. $SCF_d = f(a/w)$, assuming various damage extents, presumably in the range limited by visual and ultrasonic inspections

- Establishing CF related SCF_d to the *a*/*w* ratio by curve fitting
- Comparing the above relationships against those known for an open hole and choosing EOH dimensions based on the best match of results.

One should bear in mind that such relationships could be specific for a laminate under consideration and could differ from laminate to laminate depending on the reinforcement, matrix and stacking sequence.

Acknowledgments

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