COMPRESSION STRENGTH OF NOTCHED AND IMPACT DAMAGED COMPOSITE LAMINATES

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Abstract

The paper presents the analytical and experimental work performed on notched and impact damaged composite laminates. The objective of the study was to find out how well compression strength of carbon/epoxy-laminates can be estimated with an analytical method found from open literature [2-3].

Two laminates were selected for the study. Both are symmetric and quasi-isotropic but have different lay-ups: one with [0/60/-60] and the other with [0/45/-45/90] layer orientations. The material used in the test specimens was AS4/3501-6 unidirectional prepreg tape. All laminates had 24 plies resulting in the 3.4 mm nominal thickness. The notch geometries used were circular and elliptical holes in the middle of the specimens.

The impact tests were performed using a drop weight impact testing machine. The specimens were impacted only once. The impact energies used were 10 and 14 J. The size of the damage was defined by tap testing.

The results of the study indicate that the analysis method predicts well compression strength of the notched laminates although the method slightly underestimates the strength of the laminate with an elliptical hole and overestimates the strength of the laminate with a circular hole. The correspondence between analysis and test results of the impact damaged laminates is also good, the analysis curve representing well the average behavior of the test results. The accurate size of the impact damage was noted to be crucial information for the analysis. Regardless of the method used for NDT, a specific procedure for determining the actual damage size is required.

1 Introduction

The residual strength of impact damaged composite laminates is probably the most significant single test result representing damage tolerance of composite aircraft structures. It is possible that after impact no visible damage can be seen on the laminate surface. However, due to the low out-of-plane strength properties of the laminate, significant delaminations inside the laminate and fiber breakage on the other side of the laminate are possible. Laminate strength can be reduced to less than half of the original strength. In service, various impacts are possible to occur. Therefore, the strength reduction must be taken into account in the design of structures. Typically this is done by limiting the laminate allowable strains.

In the analysis of impact damaged laminates the damage is typically simplified to an equivalent open hole. The hole is usually assumed to be circular in shape. Analysis parameters are adjusted to match existing open hole test results. The repeatability of open hole tests is usually very good, because the test specimens are machined. Impact damages in laminates are usually different even if the impact energy is kept constant resulting in additional scatter of test results. The drawback in the equivalent hole approach is that results are typically applicable for one laminate lay-up only.

The purpose of this paper was to find out how well the compression strength of carbon/epoxy-laminates can be estimated with an analytical method found from open literature [2-3].

The analysis method is based on an assumption that the final failure of the laminate occurs when the ultimate strength of the 0° layers is exceeded. The method utilizes average stress in 0° layers and the maximum stress criterion. As in other notched laminate analyses the characteristic length is required also in this method. However, the characteristic length is considered as material property instead of laminate property.

The analysis method is applicable for both notched and impact damaged laminates and for both tension and compression loading. In the original papers there was limited data on the accuracy of the method in compression loading of notched laminates. This paper focuses on compression loading of notched and impact damaged composite laminates. The notch geometries used are elliptical and circular holes. Two different laminates are used. Both are symmetric and quasi-isotropic but have different lay-ups: one with [0/60/-60] and the other with [0/45/-45/90] layer orientations.

2 Analysis Method

The analysis method was originally developed for estimating the strength of notched laminates. The notch can be either a circular or elliptical hole. At the moment the method is applicable only for uniaxial tension or compression loading. The method was further developed to the impact damaged laminates. The purpose was to analytically expand the results of compression after impact (CAI) tests. The analysis method is presented in Refs [2] and [3]. The first describes the analysis of notched laminates and the latter the analysis of impact damaged laminates. The main equations are the same in both approaches.

2.1 Analysis of Notched Laminates

Consider an elliptical hole with semi-axes *a* and *b* in an infinite plate as presented in Fig. 1. The *xy*-coordinate system is located at the center of the hole. A uniformly distributed tensile or compressive stress $\bar{\sigma}_y$ produces a stress distribution in the 0° layer along the *x*-axis, denoted by $\bar{\sigma}_y^0(x,0)$. The 0° layer in this context refers to the layer having its fibers in the *y*-direction.

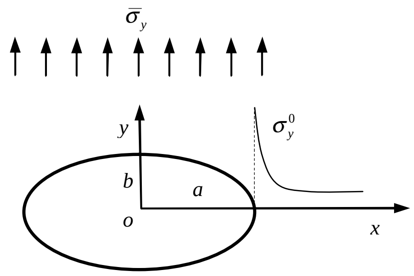

Fig. 1 Elliptical hole and loading conditions

2.1.1 Failure Stress

The method is based on an assumption that the strength of the laminate is reached when the stress in 0° layers over some distance away from the hole edge equals or exceeds the ultimate strength of a unidirectional laminate. Based on this approach the failure criterion is named as the load bearing ply failure (LBPF) criterion. It is further shown that the distance, called the characteristic length and denoted by l_0, is independent of laminate lay-up, geometry and stress distribution. This means that the characteristic length is dependent only on the material system. However, the characteristic length can be different in tension and in compression. The failure criterion is mathematically expressed as:

$$\frac{1}{l_0}\int_a^{a+l_0}\sigma_y^0(x,0)dx = X \tag{1}$$

where.

- l_0 Material system and load direction dependent characteristic length
- a Length of the semi-axis of the ellipse, R in case of a circular notch
- X Longitudinal ultimate strength of the unidirectional laminate, X_t for tension X_c for compression

The derivation of the notched laminate failure stress is based on the complex potential method presented in Ref. [4]. The derivation is not presented in this paper; full details can be found in Refs [2] and [3]. The failure stress of the notched laminate can be obtained from:

$$\sigma_N = \frac{l_0 X}{\alpha_1 F_1 + \alpha_2 F_2 + \alpha_3 F_3} Y \qquad (2)$$

where Y is the finite width correction factor and the terms F_i are:

$$F_1 = \int_a^{a+l_0} \left\{ 1 + a\,\mathrm{Re}\left[\frac{(a - i\mu_2 b)\mu_1 \mu_2^2}{(\mu_1-\mu_2)(x+\sqrt{x^2-a^2-\mu_2^2 b^2})\sqrt{x^2-a^2-\mu_2^2 b^2}} - \right.\right.$$
$$\left.\left. - \frac{(a - i\mu_1 b)\mu_1^2 \mu_2}{(\mu_1-\mu_2)(x+\sqrt{x^2-a^2-\mu_1^2 b^2})\sqrt{x^2-a^2-\mu_1^2 b^2}} \right]\right\} dx$$
$$F_2 = a \int_a^{a+l_0} \left\{ \mathrm{Re}\left[\frac{(a - i\mu_2 b)\mu_1}{(\mu_1-\mu_2)(x+\sqrt{x^2-a^2-\mu_2^2 b^2})\sqrt{x^2-a^2-\mu_2^2 b^2}} - \right.\right.$$
$$\left.\left. - \frac{(a - i\mu_1 b)\mu_2}{(\mu_1-\mu_2)(x+\sqrt{x^2-a^2-\mu_1^2 b^2})\sqrt{x^2-a^2-\mu_1^2 b^2}} \right]\right\} dx$$
$$F_3 = -a \int_a^{a+l_0} \left\{ \mathrm{Re}\left[\frac{(a - i\mu_2 b)\mu_1 \mu_2}{(\mu_1-\mu_2)(x+\sqrt{x^2-a^2-\mu_2^2 b^2})\sqrt{x^2-a^2-\mu_2^2 b^2}} - \right.\right.$$
$$\left.\left. - \frac{(a - i\mu_1 b)\mu_1 \mu_2}{(\mu_1-\mu_2)(x+\sqrt{x^2-a^2-\mu_1^2 b^2})\sqrt{x^2-a^2-\mu_1^2 b^2}} \right]\right\} dx \qquad (3)$$

The terms a and b define the geometry of the ellipse (Fig. 1), and μ_1 and μ_2 are the roots of the characteristic equation. Tthe terms α are:

$$\begin{aligned} \alpha_1 &= Q_{11} a_{11}^* + Q_{12} a_{12}^* \\ \alpha_2 &= Q_{11} a_{12}^* + Q_{12} a_{22}^* \\ \alpha_3 &= Q_{11} a_{16}^* + Q_{12} a_{26}^* \end{aligned} \qquad (4)$$

where Q_{ij} are the elements of the laminate stiffness matrix and a_{ij} the elements of the normalized compliance matrix. The authors fo Refs. [2] and [3] propose that the finite width correction factor for isotropic plates can be used if the ratio of the hole diameter to the plate width is less than ⅓. The finite width correction factor for a circular hole is then [5]:

$$Y = \frac{3\left(1 - \frac{2R}{W}\right)}{2 + \left(1 - \frac{2R}{W}\right)^3} \qquad (5)$$

where R is the hole radius and W is the specimen width. For an elliptical hole the correction factor is [6]:

$$Y = \frac{\lambda^2}{(1-\lambda)^2} + \frac{1-2\lambda}{(1-\lambda)^2}\sqrt{1 + (\lambda^2 - 1)\left(\frac{2a}{W}M\right)^2} - $$
$$- \frac{\lambda^2}{1-\lambda}\left(\frac{2a}{W}M\right)^2 \left[1 + (\lambda^2-1)\left(\frac{2a}{W}M\right)^2\right]^{-\frac{1}{2}} \qquad (6)$$

where

$$M = \frac{\sqrt{1 - 8\left[\frac{3\left(1-\frac{2a}{W}\right)}{2+\left(1-\frac{2a}{W}\right)^3} - 1\right]} - 1}{2\left(\frac{2a}{W}\right)^2} \qquad (7)$$

$$\lambda = \frac{b}{a}$$

2.1.2 Characteristic Length

As mentioned before the characteristic length is material system dependent. However, the original references do not specify what kind of test program should be used to determine the value for the characteristic length. The tests should be performed on the laminate level, not on the ply level.

The characteristic length is different for tension and compression loading. This is due to the fact that the damage mechanisms in tension and in compression are different. In tension the angle ply layers damage due to matrix cracking. This typically reduces the stress concentration in the 0° layers. In compression the damaged angle ply layers provide less support for 0° layers and fiber microbuckling occurs at lower loads reducing the ultimate failure load of the laminate.

2.2 Analysis of Impact Damaged Laminates

The analysis of impact damaged laminates is based on the equations presented for the notched laminate. The impact damage is modeled as an equivalent elliptical hole. The extension of the analysis method to impact damages is presented in Ref. [3]. The authors propose that in the equivalent elliptical hole the width of the hole is the same as the width of the damaged area. The height of the hole is the same as the height of the dent caused by the impact. The principle is illustrated in Fig 2.

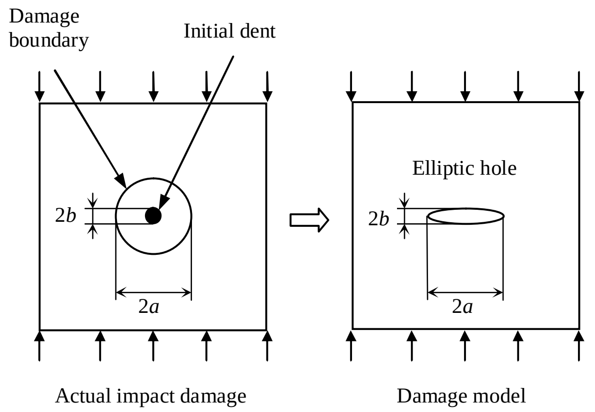

Fig. 2. Impact damage and equivalent hole

3 Test Arrangements

The tests were performed according to the compression after impact (CAI) testing standard AITM 1.0010 Ref. [1]. The same standard was applied to both notched and impact damaged specimens, i.e. the same specimen geometry and test arrangements were used in all tests.

3.1 Test Specimens

According to the CAI standard the dimensions of the test specimen are 100×150 mm, the stacking sequence is quasi-isotropic and the laminate thickness is as close to 4 mm as possible. The thickness of the laminate was reduced to 3.4 mm due to the limited loading capacity (100 kN).

Two different quasi-isotropic laminates were used: 1) [3(0/45/-45/90/90/-45/45/0)] and 2) [4(0/60/-60/-60/60/0)]. The total amount of plies was 24 in both laminates. The in-plane properties of the laminates are equal but bending properties are different. It is expected that due to the different bending properties the mechanical behavior is different during impact resulting in different damage sizes and shapes.

Four different notch geometries were used in the tests: two circular holes and two elliptical holes. The notch geometries are presented in Table 1.

The impact energies were determined experimentally based on previous experience and the resulting damage size. The impact energies selected for the tests were 10J and 14J.

Table 1. Notch geometries used in tests

Notch	Width [mm]	Height {mm]	Width/ height
P1	25	25	1
P2	36	36	1
E1	25	12.5	2
E2	36	12	3

3.3 Specimen Manufacture

The specimens were manufactured from the AS4/3501-6 carbon/epoxy prepreg. Laminates were laid up onto a flat aluminum mold. Debulking was performed after three layers during the lay-up. Ten 340×340 mm panels were manufactured.

The panels were cured in an autoclave. The cure temperature was 180°C and the curing time was 2 hours. The cure cycle included a dwell period of 1 hour at 120°C. The autoclave pressure was 5.5 bars.

The test specimens were machined from the panels using an NC-machine. Six specimens were machined from each laminate panel, i.e. one specimen for each test series. The machined specimens are shown in Fig. 3.

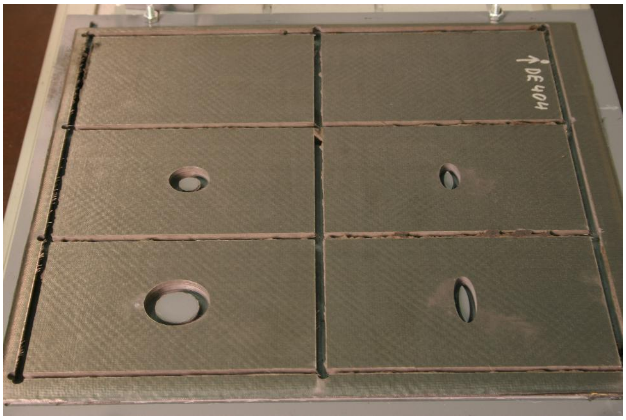

Fig. 3 Specimens machined from a laminate panel

3.4 Test Equipment

The impact tests were performed using a drop weight impact testing machine. The testing machine fulfills the requirements set by the testing standard. The machine is equipped with a catcher that prevents multiple impacts on the specimen. The principle of the testing machine is presented in Fig. 4 and the actual hardware in Fig. 5. The impactor weights and drop heights used in the tests are presented in Table 2.

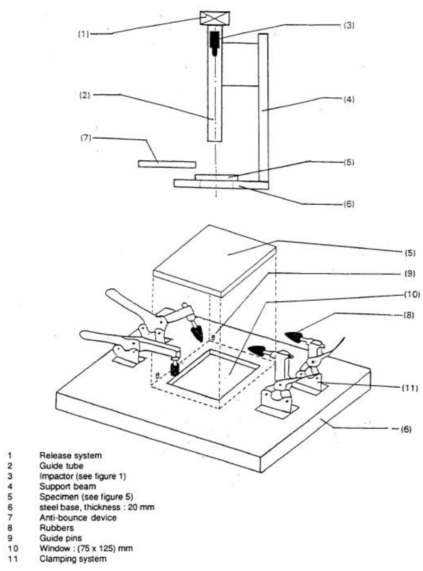

Fig. 4. Principle of the impact testing machine [1].

Fig. 5.The impact testing machine used in the tests.

Table 2. Impactor weights and drop heights

Impact	Impact Energy [J]	Drop Weight [kg]	Drop Height [m]
I1	10	1.702	0.599
I2	14	2.079	0.686
I2	14	1.702	0.837

The 2.079 kg drop weight was used only in one impact test for both laminate types since the impact caused fiber breakage on the opposite side of the laminate. This was an unfavorable effect and therefore the mass of the impactor was reduced for other impacts. The impactor head was hemispherical with 16 mm diameter.

The compression load was applied to the specimens using a hydraulic uniaxial testing machine with the maximum loading capacity of 100 kN. A compression after impact test fixture preventing the specimen global buckling was used in the tests. The fixture is presented in Fig. 6.

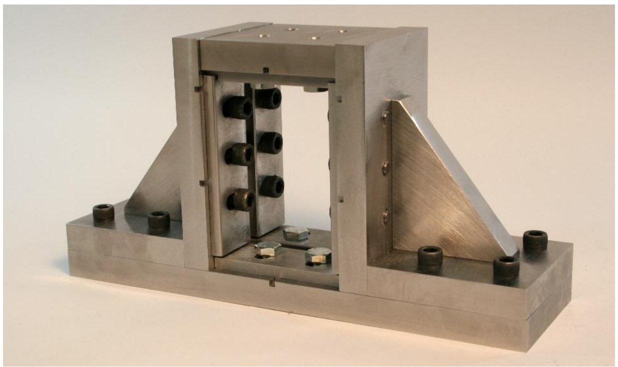

Fig. 6 CAI test fixture used in the tests

3.5 Test Matrix

The test matrix is shown in Table 3. The test matrix presents the number of specimens for different laminate types and notch/damage sizes.

Table 3. The test matrix

	Laminate Structure	
	[3(0/45/-45/90/ 90/-45/45/0)]	[4(0/60/-60/ -60/60/0)]
Ellipse E1	5	5
Ellipse E2	5	5
Circular P1	5	5
Circular P2	5	5
Impact I1	5	5
Impact I2	5	5
Total	30	30

4 Test Results

4.1 Elliptical Holes

The measured failure stresses of the specimens with an elliptical hole are presented in Tables 4 and 5. The tables present the average gross stress and the standard deviations for both laminate types. It can be seen that with both notch sizes the [0/60/-60] –type laminate gives a higher failure stress than the [0/45/-45/90] –type laminate. However, it must be noticed that three of the specimens in the test series E1 did not break in the notch area but at the upper edge of the specimen. This is illustrated in Fig. 7 as well as the typical failure for other specimens. In the typical failure, the surface layers are buckled with partially broken fibers. The edge failure occurred only with the [0/60/-60] –type laminate. Despite of the incorrect failure mode, all specimens are included in the average failure stress.

Table 4. Test results of specimens with small elliptical hole, 2*a* = 25 mm, *a*/*b* = 2

	Failure Stress	Deviation	
	[MPa]	[MPa]	%
[0/60/-60]	243.1	10.1	4.2
[0/45/-45/90]	228.9	14.1	6.2

Table 5. Test results of specimens with large elliptical hole, 2*a* = 36 mm, *a*/*b* = 3

	Failure Stress	Deviation	
	[MPa]	[MPa]	%
[0/60/-60]	202.4	13.3	6.6
[0/45/-45/90]	190.4	14.9	7.8

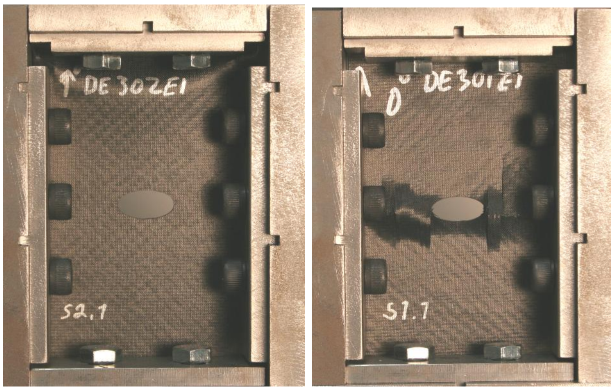

Fig. 7. Failure at the upper edge of the specimen (left), typical specimen failure in the notch area (right).

4.2 Circular Holes

The measured failure stresses of the specimens with a circular notch are presented in Tables 6 and 7. The test results are similar to the results of the specimens with elliptical holes. The [0/60/-60] –type laminate gives a higher failure stresses than the [0/45/-45/90] –type laminate. For the larger circular hole, the deviation in the test results is very small.

Table 6. Test results of specimens with a small circular hole, *D* = 25 mm.

	Failure Stress	Deviation	
	[MPa]	[MPa]	%
[0/60/-60]	258.8	16.4	6.3
[0/45/-45/90]	238.7	14.6	6.1

Table 7 Test results of specimens with a large circular hole, *D* = 36 mm.

	Failure Stress [MPa]	Deviation [MPa]	%
[0/60/-60]	224.3	8.1	3.6
[0/45/-45/90]	205.3	3.0	1.5

4.3 Impact Damaged Laminates

The measured failure stresses of impact damaged specimens are presented in Tables 8 and 9. All specimens failed at the center within the damaged area.

The average size of the damage for both impact energies and laminate types is presented in Table 10. It is noticeable that the average damage width is practically the same for both impact energies in the [0/60/-60] –type laminate. However, the higher impact energy can be observed in the dent height and depth that are clearly larger. With the [0/45/-45/90] –type laminate the damage width is also larger for the higher impact energy.

In the evaluation of the results it must be kept in mind that the damage size was determined using tap testing which cannot be considered as a fully reliable method. The dent height was measured visually using a digital caliper and the depth was determined according to the standard.

Table 8. Test results of impact damaged specimens, impact energy 10J.

	Failure Stress [MPa]	Deviation [MPa]	%
[0/60/-60]	183.8	6.0	3.3
[0/45/-45/90]	194.8	3.6	1.8

Table 9. Test results of impact damaged specimens, impact energy 14J.

	Failure Stress [MPa]	Deviation [MPa]	%
[0/60/-60]	170.7	6.7	3.9
[0/45/-45/90]	161.3	7.4	4.6

Table 10. Average characteristics of impact damages.

	Impact	Damage width [mm]	Dent height [mm]	Dent depth [mm]
[0/60/-60]	10J	23.3	5.6	0.2
[0/60/-60]	14J	23.8	9.8	0.5
[0/45/-45/90]	10J	26.5	6.3	0.2
[0/45/-45/90]	14J	29.0	8.2	0.6

4.4 Summary of the Test Results

Fig. 8 summarizes the test results. The figure clearly shows that the [0/60/-60] –type laminate gives a higher failure stress except in the 14J impact energy test series. For comparison, the measured compression strength of the [0/45/-45/90] –type laminate is added to the figure.

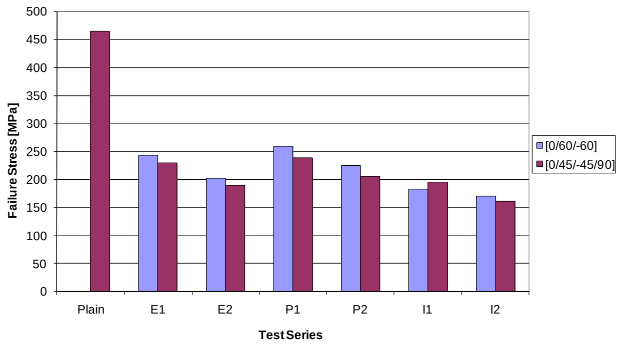

Fig. 8. Summary of the test results.

5 Analysis vs. Test Results

5.1 Notched Laminates

Fig. 9 presents the measured failure stresses of the notched specimens and the corresponding analysis results. The analysis method provides same results to both laminates because the in-plane properties for the laminates are the same.

The characteristic length used in the analysis was l_0 = 2.426. This is the value that was used in Ref. [3] for the same material. Originally the value was generated for the AS4/3502 material [3].

It can be noticed that the analysis method underestimates the failure stress of laminates with an elliptical hole and overestimates the failure stress of the laminates with a larger circular hole. With the smaller circular hole the analysis result is in between the test results. The percentual error between analysis and test results is presented in Fig 10. It shows graphically the difference between the analysis and average test results.

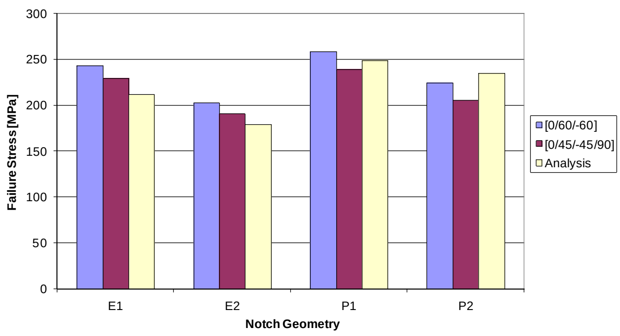

Fig. 9. Analysis vs. test results for notched laminates.

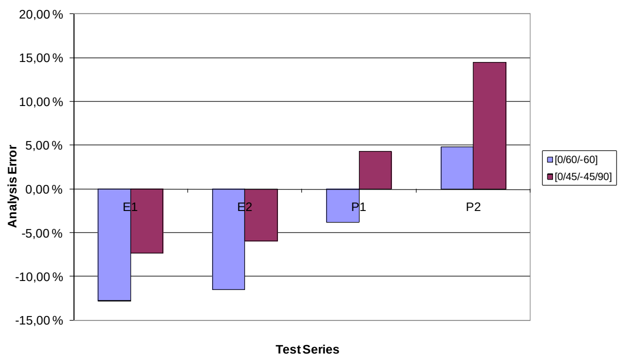

Fig. 10. Percentual analysis error to the average test result.

5.2 Impact Damaged Laminates

The individual test results from impact damaged specimens and the estimated failure stress as a function of the damage width are presented in Fig. 11. The analysis curve fits well to the overall behavior of test results.

When comparing test series separately to the analysis curve it can be seen that the analysis method overestimates the failure stress of the [0/60/-60] –type laminate and underestimates the failure stress of the [0/45/-45/90] –type laminate. However, the test results of the [0/45/-45/90] –type laminate with the 14J impact are very close to the analysis curve. Again, it must be kept in mind that the damage size was determined using tap testing and the inspection is very much dependent on the inspector.

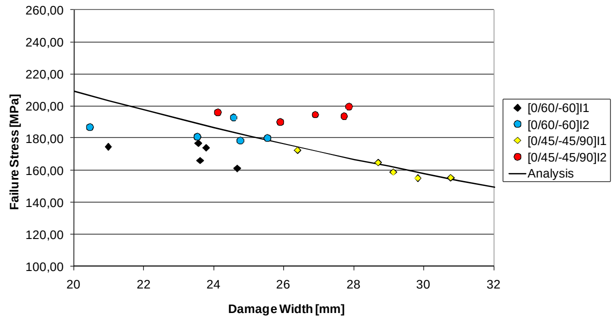

Fig. 11. Test results of impact damaged specimens and the analysis result as a function of damage width.

5 Conclusions

Based on the work performed the following conclusions can be made

- The test series performed were successful providing reference strength data for two quasi-isotropic laminate lay-ups in open hole compression and in compression after impact.
- The failure stresses were higher for the [0/60/-60] –type laminate than for the [0/45/-45/90] –type laminate except in the case of the larger circular hole.
- In the test series of the [0/60/-60] –type laminate with the smaller elliptical hole most specimens (3/5) failed at the upper edge of the specimen. Therefore, the failure strength was not reliably measured. However, the failure stresses are of the same of order of magnitude for all specimens in this test series.
- The analysis results correspond well with the test results when comparing with the overall behavior.
- The analysis method underestimates the failure strength of laminates with an elliptical hole and overestimates the failure strength of the laminates with a circular hole.
- When comparing the analysis results to test results of impact damaged specimens it can be noticed that the method underestimates

the failure stress of the [0/45/-45/90] –type laminate with 10J impact damage and slightly overestimates the failure stress of all [0/60/-60] –type specimens. The test results of the [0/45/-45/90] –type laminate with a 14J impact lie exactly along the analysis curve.

- The size of the impact damage was determined using tap testing. The result is very dependent on the inspector and it has a significant effect on the analysis results.
- Regardless of the method used for NDT, a specific procedure for determining the actual damage size is required.
- The effect finite width correction factor was not studied here. In case of the large hole the width of the hole with respect to the specimen width exceeds the recommendation for the correction factor (⅓). The effect of using isotropic correction factor in these cases should be studied in detail.
- The analysis method found from open literature is a very useful tool for estimating notched or compression after impact strength of laminates. It can be used to extend existing test results to cover wider area of laminate lay-ups.

Acknowledgements

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References

[1] Determination of Compression Strength after Impact, *Airbus Industrie Test Method, Fiber Reinforced Plastics, AITM 1.0010*, Issue 2, June 1994, 11 p.

[2] Chen P., Shen Z., Wang J.Y., Prediction of hte Strength of Notched Fiber-Dominated Composite Laminates. *Composite Science andTechnology*, vol 61, 2001, Elsevier Science Ltd. 1311-1321.

[3] Chen P., Shen Z., Wang J.Y., A New Method for Compression After Impact Strength Prediction of Composite Laminates. *Journal of Composite Material*, vol 36, No. 5/2002. Sage Publications. 589-610.

[4] Lekhnitskii S.G., *Anisotropic Plates*, Gordon and Breach Science Publishers, New York, 1968. 534 p.

[5] Pilkey W.D., *Peterson's Stress Correction Factors*, second edition. John Wiley & Sons Inc, New York, 1997, 508 s.

[6] Tan S.C., *Stress Concentrations in Laminated Composites*. Lancaster Technomic, 1994.

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