FATIGUE RESISTANCE OF COMPOSITE FIBRE-METAL LAMINATES SUBJECTED TO IMPACT LOADING

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ABSTRACT

In order to investigate the damage tolerance of composite fibre-metal laminates (GLARE®) to impact and post-impact fatigue loading, series of impact and fatigue tests were carried out on three types of laminates. Damage in GLARE® laminates due to impact loading as well as damage propagation in fatigue were monitored and analysed. Potential strength reduction due to accumulated damage was also investigated.

In general, GLARE® laminates showed excellent resistance to dynamic impact and fatigue loading. Impact induced delaminations did not show any increase under cyclic loading; whereas the fatigue growth of cracks was controlled by fiber-bridging effect. The residual strength of laminates with through-the-thickness impact damage was conservatively predicted based on calculation of the residual strength of laminates with through-the-thickness notches.

1. INTRODUCTION

Nowadays, various transport aircraft face the operating challenge because of accidental in-service damage of aircraft structures due dynamic low and high velocity impacts. The aircraft structure should be damage tolerant with respect to dynamic impact loads. This means the fuselage structure should be able to withstand impact damages without reducing the structural integrity below allowable limits. Since in-service maintenance is very important, this explains why a structural material, which has good impact resistance, offers fewer repairs after impact and requires fewer inspections, is welcomed. The introduction of composite fiber-metal laminates, in particular GLARE® (GLAss REinforced), as a skin material for the upper and side shells in the forward and rear fuselage body of Airbus A380, as shown in Fig. 1, allows a new approach to the existing maintenance procedures, in particular, because of less restrictive allowable damage limits (i.e. damage for which a structural repair is not necessary, and/or justified with an inspection interval the structure can be operated).

Figure 1: Application of GLARE® on A380 (status 2008).

This composite material consists of thin layers of aluminium sheets and unidirectional prepreg layers of glass fibres embedded into an epoxy based matrix. GLARE® demonstrates excellent resistance to fatigue crack growth, high tolerance to accidental damage, and superior residual strength in comparison with monolithic aerospace aluminium alloys used for structural applications.

In general, the following types of damage in GLARE® laminates occur due to dynamic impact loading [1]:

- Dents with various depths and widths due to plastic deformation of the aluminium layers; however, with no cracking in aluminium layers. It is known that, depending on the amount of impact energy, delaminations, fiber fracture, and matrix cracking in the vicinity of laminate could be induced.
- Dents with one outer aluminium layer cracked. Hereafter, this type of damage is referred to as *First Crack* (FC). Due to low velocity impact (LVI) loading, the outer Al layer on the non-impacted, i.e. convex, side will be cracked in most cases.
- Dents with damage through the entire laminate thickness. Hereafter, this type of damage is referred to as *through-the-thickness* (TTT) *crack*.

Significant research into the impact behaviour of fibre-metal laminates has been documented in the literature [1-4]. There has however been limited published work on the fatigue behaviour of GLARE® subjected to dynamic impact loading [5,6]. Therefore, further work on the fatigue resistance of fibre-metal laminates following impact loading has been required. This paper presents the results of an experimental investigation into the effect of low velocity impact loading on the fatigue performance of GLARE® laminates and their residual strength.

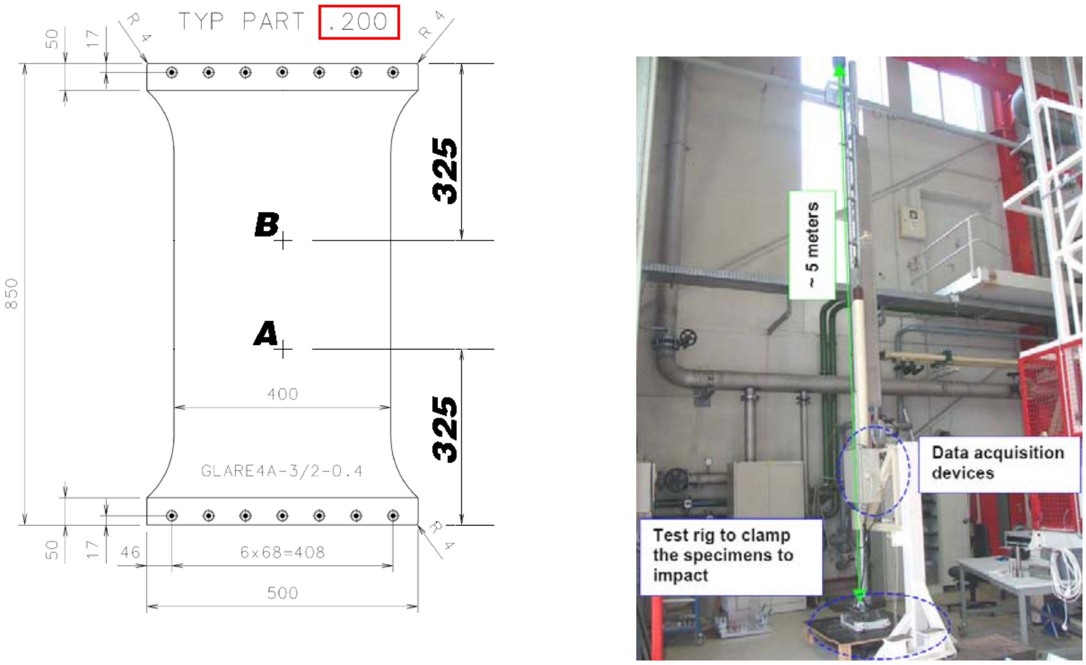
2. EXPERIMENTAL PROCEDURE

A number of specimens was manufactured according to the matrix in Table 1 and the specimen geometry shown in Fig. 2(a).

Table 1: Specimen matrix.

Specimen group	**N° of specimens**	**Laminate lay-up**	**Thickness (mm)**
200	6	GLARE4A-3/2-0,4	1,95
202	12	GLARE4A-4/3-0,4	2,8
204	12	GLARE4A-5/4-0,4	3,6

In the notation GLARE4A-3/2-0,4, 4A means 0°/90°/0° composite prepreg build-up sequence between two aluminium sheets regarding the aluminium rolling direction; 3/2 means the number of aluminium layers/composite lay-ups; 0,4 means the thickness of aluminium sheets in mm.



(a) *(b)*

Figure 2: (a) Specimen geometry; (b) Experimental set-up for dynamic impact tests.

Two low velocity dynamic impacts were applied per specimen (locations *A* and *B* as per Fig.2(a)) using an impact drop tower, as demonstrated in Fig. 2(b), with the help of a spherical impactor (radius R=8 mm; mass 4 kg).

After the specimens were impacted, they were subjected to fatigue loading (constant amplitude, maximum 120 000 cycles, stress ratio R = 0.1, frequency of 10 Hz, room temperature). Fatigue stress levels were comparable with the one corresponding to the maximum fatigue allowable.

Before the fatigue tests, the impacted locations of the specimens were inspected on the presence of impact induced cracks in the outer aluminium layers and delaminations. The size and shape of delaminations were assessed by manual through transmission Ultrasounds Test (UT); whereas, the presence and length of cracks in the aluminium layers were inspected by High Frequency Eddy Current Test (HFET). In addition, the extent of impact damage as well as the initiation of fatigue induced cracks were monitored on the impacted specimens during and after fatigue loading.

After the fatigue tests were completed, several specimens were tested in quasi-static tension till failure in order to analyse the influence of impact and fatigue damage on the residual strength of GLARE$^{®}$ laminates.

3. RESULTS AND DISCUSSION

3.1 Impact test results

The impact test results are presented as measured dent depth after impact vs impact energy in Fig.3 (a), delamination area vs impact energy in Fig.3 (b), and dent depth vs delamination area in Fig.3 (c), correspondently.

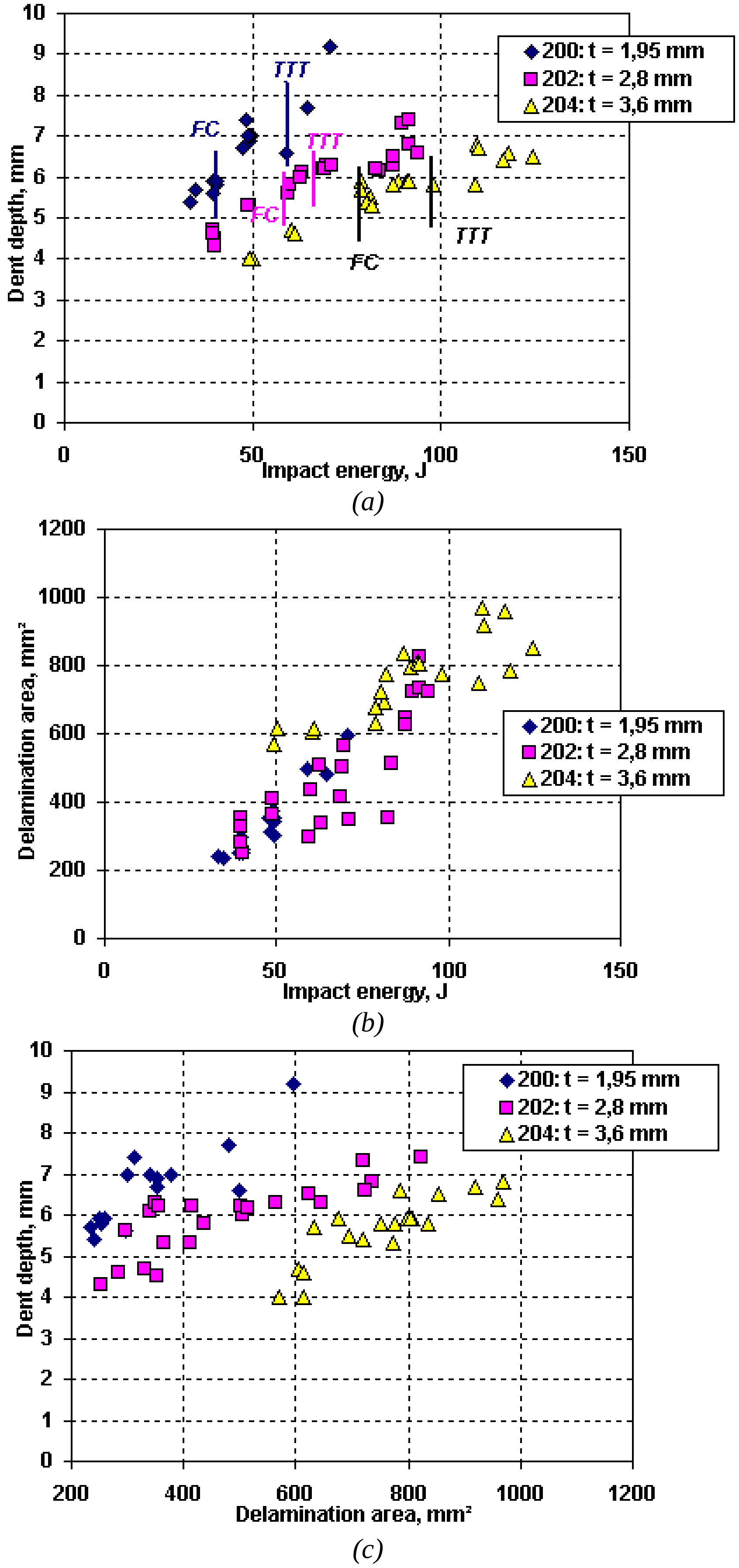


Figure 3: Impact test results.

In general, the impact response data in Fig.3 (a) show more or less linear relationship between the applied impact energy and the depth of induced dent deformation. Indeed, the thicker laminate was, the more energy was required in order to introduce dents with the same depth. In the same plot, the boundaries between different extent of impact damage induced to the laminates are marked, i.e. *FC* for first crack damage and *TTT* for through-the-thickness damage. As seen, for the range of dent depth between 5 and 6 mm, one could expect the presence of impact crack in the non-impacted side of the laminate. For the dent depth deeper than 6 mm there is high probability of having through-the-thickness impact damage.

Figure 3 (b) shows that the area of detected delaminations with regard to the applied impact energy was rather not depended on the laminate thickness. However, as Fig.3 (c) shows, there was difference in the delamination size detected in the laminates having similar dent depth. Indeed, to introduce the same dent depth in 1,95 and 3,6 mm thick laminates, more energy required in the latter case, causing larger delaminations in the thick laminate.

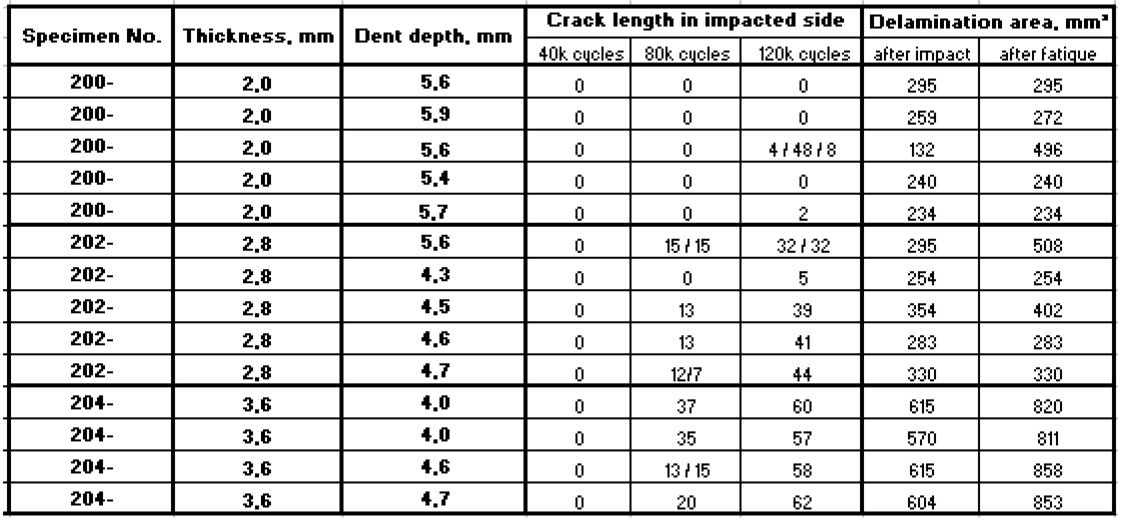
3.2 Fatigue test results

The obtained fatigue test results are divided into three groups depending on the impact damage experienced by the specimens.

Specimens with dents

Table 2 presents the results of crack and delamination inspection during and after the fatigue tests. As seen, in several specimens cracks initiated and propagated.

Table 2: Crack and delamination NDI results for specimens with dent damage.



Specimen No.	**Thickness, mm**	**Dent depth, mm**	**Crack length in impacted side**			**Delamination area, mm^2**	
			40k cycles	80k cycles	120k cycles	after impact	after fatigue
200-	**2,0**	**5,6**	0	0	0	295	295
200-	**2,0**	**5,9**	0	0	0	259	272
200-	**2,0**	**5,6**	0	0	4 / 48 / 8	132	496
200-	**2,0**	**5,4**	0	0	0	240	240
200-	**2,0**	**5,7**	0	0	2	234	234
202-	**2,8**	**5,6**	0	15 / 15	32 / 32	295	508
202-	**2,8**	**4,3**	0	0	5	254	254
202-	**2,8**	**4,5**	0	13	39	354	402
202-	**2,8**	**4,6**	0	13	41	283	283
202-	**2,8**	**4,7**	0	12/7	44	330	330
204-	**3,6**	**4,0**	0	37	60	615	820
204-	**3,6**	**4,0**	0	35	57	570	811
204-	**3,6**	**4,6**	0	13 / 15	58	615	858
204-	**3,6**	**4,7**	0	20	62	604	853

These cracks usually initiated in the dented area on the impacted side of the specimens. No crack initiation on the non-impacted side was reported. In general, in those specimens where no cracking occurred in fatigue, the original size of delamination did not increase under cycling loading. In the specimens where fatigue cracks initiated and propagated, there was certain increase in the delamination size (see an example in Fig. 4).

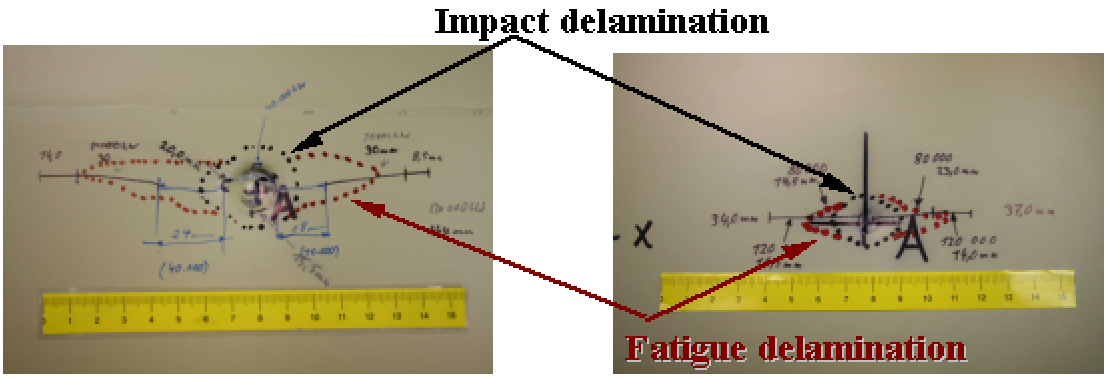


Figure 4: Delaminations due to impact and crack bridging effect.

This was due to the general bridging effect of cracks propagating in fiber-metal laminates (see Fig. 5).

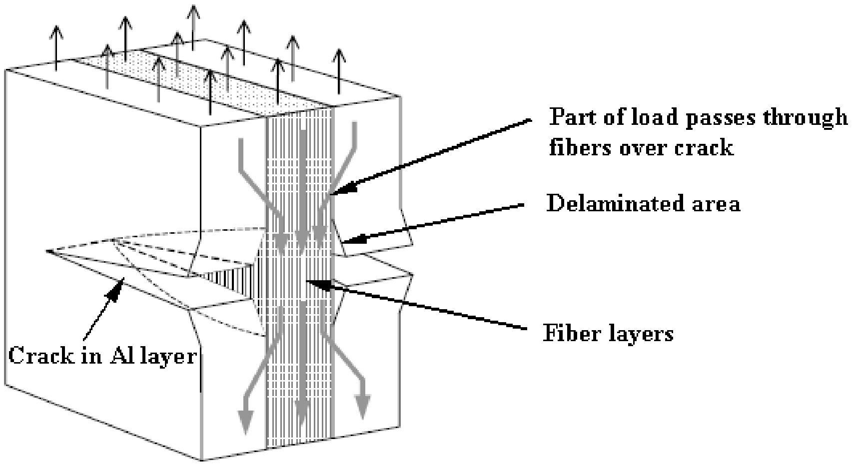


Figure 5: Crack bridging effect.

The intact fiber layers are slowing the crack propagation since a part o f the applied load is transferred through them in the wake of the crack. This results in shear stress on the interface between the composite fiber and aluminium layers. Under cycling loading, this shear stress will result in the appearance of delamination along the crack edges. Altogether, this results in the stress intensity factor is significantly reduced and the fatigue crack growth becomes slow. It has been proved that the fatigue behaviour of fiber metal laminates is strongly affected by the delamination resistance of the fibre/adhesive layers [8].

Specimens with first crack impact damage

An example of first crack damage is shown in Fig. 6.

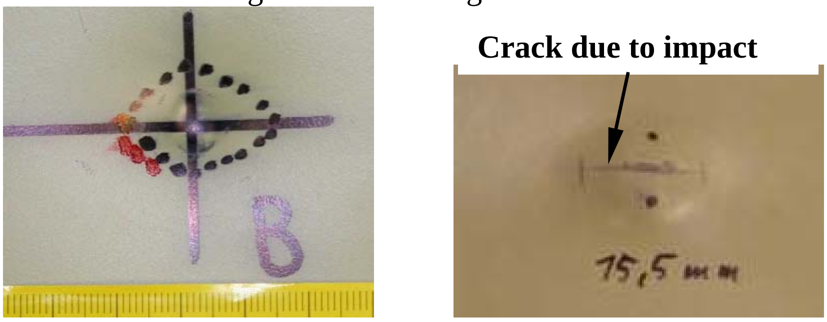
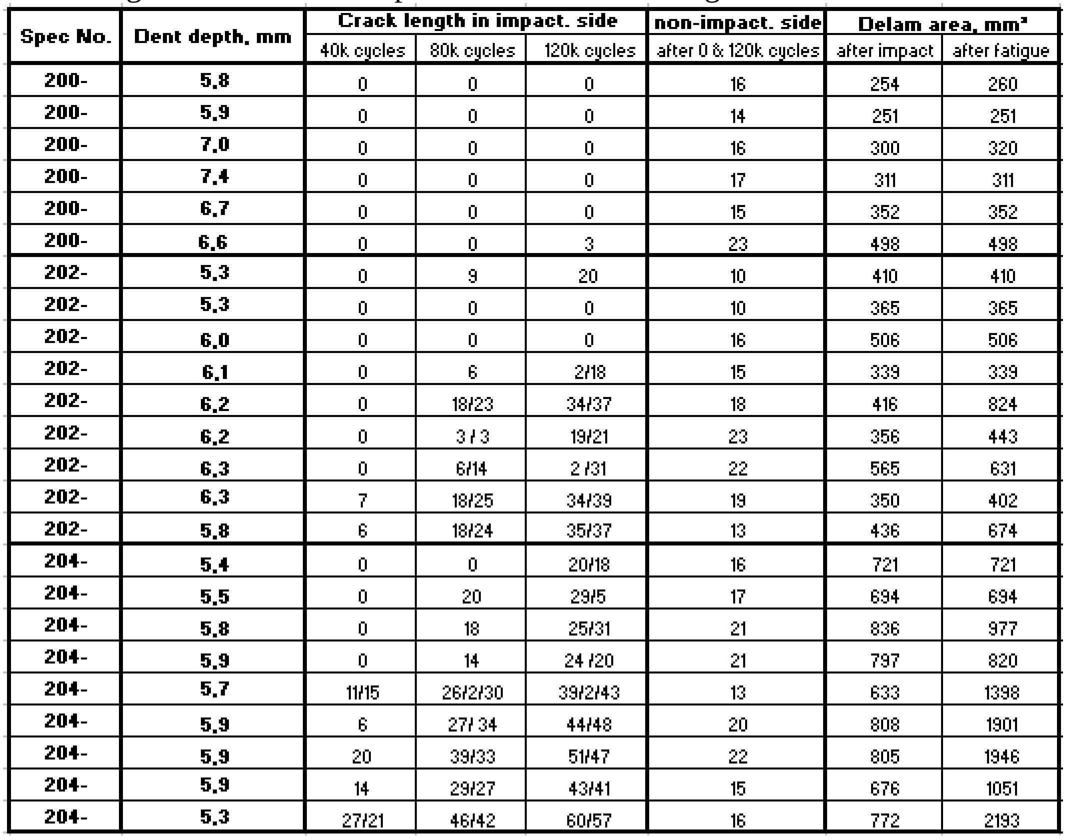


Figure 6: Dent with first crack damage after fatigue: impacted side (left) and non-impacted side (right).

The fatigue results of the specimens with FC impact damage are presented in Table 3.

Table 3: Fatigue NDI results for specimens with FC damage.



Spec No.	Dent depth, mm	Crack length in impact. side			non-impact. side	Delam area, mm^2	
		40k cycles	80k cycles	120k cycles	after 0 & 120k cycles	after impact	after fatigue
200-	**5,8**	0	0	0	16	254	260
200-	**5,9**	0	0	0	14	251	251
200-	**7,0**	0	0	0	16	300	320
200-	**7,4**	0	0	0	17	311	311
200-	**6,7**	0	0	0	15	352	352
200-	**6,6**	0	0	3	23	498	498
202-	**5,3**	0	9	20	10	410	410
202-	**5,3**	0	0	0	10	365	365
202-	**6,0**	0	0	0	16	506	506
202-	**6,1**	0	6	2/18	15	339	339
202-	**6,2**	0	18/23	34/37	18	416	824
202-	**6,2**	0	3 / 3	19/21	23	356	443
202-	**6,3**	0	6/14	2 /31	22	565	631
202-	**6,3**	7	18/25	34/39	19	350	402
202-	**5,8**	6	18/24	35/37	13	436	674
204-	**5,4**	0	0	20/18	16	721	721
204-	**5,5**	0	20	29/5	17	694	694
204-	**5,8**	0	18	25/31	21	836	977
204-	**5,9**	0	14	24 /20	21	797	820
204-	**5,7**	11/15	26/2/30	39/2/43	13	633	1398
204-	**5,9**	6	27/ 34	44/48	20	808	1901
204-	**5,9**	20	39/33	51/47	22	805	1946
204-	**5,9**	14	29/27	43/41	15	676	1051
204-	**5,3**	27/21	46/42	60/57	16	772	2193

As was already discussed above, the delamination increase during fatigue testing was due the fiber-bridging effect and the appearance of the corresponding delaminations. As seen in the table, those cracks, which were induced on the non-impacted side (i.e. first crack damage), did not grow under cyclic loading. After an impact load fiber-metal laminate springs back, but residual stresses remain due to plastic deformation of the Al layers as schematically shown in Fig. 7.

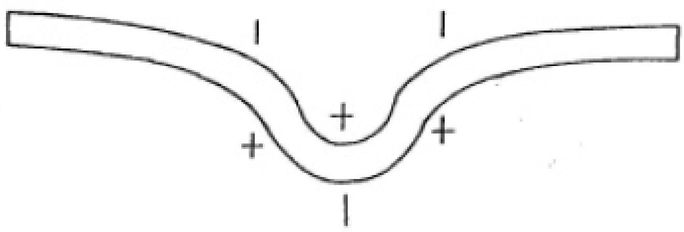


Figure 7: Residual stresses in laminate after an impact load.

When the laminate was subjected to tension fatigue, the non-impacted side remained in compression. Therefore, the crack induced in the outer Al layer on the non-impacted side was in compression and did not grow under cyclic loading.

<u>Specimens with through-the-thickness impact damage</u>

The fatigue test results of the specimens with TTT impact damage are presented in Table 4.

Table 4: Fatigue results for specimens with TTT impact damage.

Spec No.	Dent depth, mm	Crack length in impact. side				non-impact. side	Delam. area, mm^2	
		0 cycles	40k cycles	80k cycles	120k cycles	after 0 & 120k cycles	after impact	after fatigue
200-	7,0	10	14	14	14	25	377	377
200-	6,9	8,5	12	12	145/145/12	21	354	387
200-	7,0	8	9	9	9/27/22	21	341	428
200-	9,2	29/11	8/11	114/11	139 /11	38 / 10	597	1044
200-	7,7	22	77	115	137	39	480	1203
202-	7,3	17	17	19	22/2	30	721	721
202-	7,4	19	22	25	44	31	824	824
202-	6,2	13,5	14	10/14/4	26/14/26/8	27	515	563
202-	6,2	8,5	9	9 /9	28/9/26	21	503	560
202-	6,6	19,5	26	59	96	31	725	1500
202-	6,8	18,5	42	83	111	33	735	1816
202-	6,3	13	22	27 / 44	46 / 67	31	644	1673
202-	6,5	14,5	34	78	113	31	625	1741
204-	6,7	10	10	10/26/7	10/36/25	25	918	1236
204-	6,8	9,5	10	10/21	10/34/23	27	970	1173
204-	5,8	7	7/22	4 / 7/35	57/7/52	23	751	2003
204-	5,8	9,5	10	70	104	27	776	1829
204-	6,5	14,5	17/9	44/34	61/50	32	797	2220
204-	6,5	14,5	18/23	41/49	58/65	32	854	2151
204-	5,5	5,5	25/6/29	49/6/48	62/6/62	21	860	2614
204-	6,4	13,5	70	109	135	31	961	2908
204-	6,6	15,5	77	113	138	32	786	2779

As seen, the length of cracks observed on the non-impacted side did not increase under fatigue. By the end of cycling testing, multiple cracks were detected around dents on several specimens. There was no clear relationship between the initial amount of introduced damage and the appearance of multiple cracks. As was already discussed above, the increase in the delamination size was associated with the bridging effect of cracks propagated under fatigue loading. Figure 8 shows the measurement results of cracks on the impacted side for selected specimens where most crack increase was observed during cyclic loading.

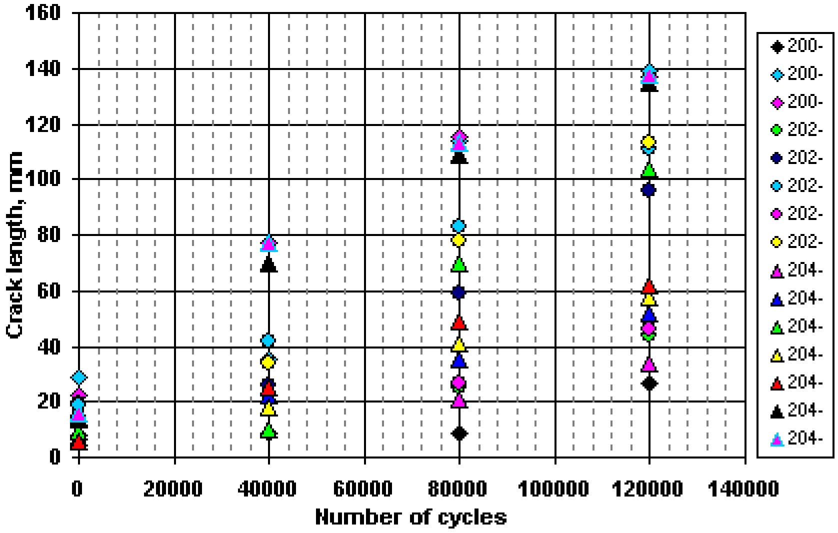


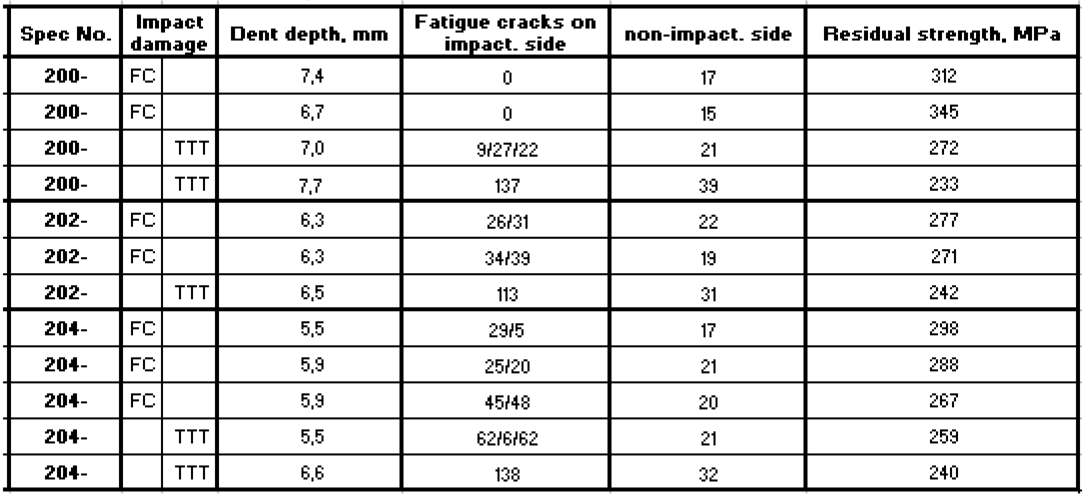
Figure 8: Measurement results of crack length on impacted side.

As can be noticed, the growth of all inspected cracks was rather linear. This was due to the aforementioned fibre-bridging effect. Therefore, by the end of the cyclic testing none of the specimens with through-the-thickness impact and corresponding accumulated fatigue damage showed catastrophic failure development. The same is true in the case of the tested specimens with dent and FC type damages.

3.3 Residual strength test results

Several specimens with first crack and through-the-thickness damage were tested in quasi-static tension till failure in order to obtain their residual strength. The corresponding results are presented in Table 5.

Table 5: Residual strength test results.



Spec No.	Impact damage		Dent depth, mm	Fatigue cracks on impact. side	non-impact. side	Residual strength, MPa
200-	FC		7,4	0	17	312
200-	FC		6,7	0	15	345
200-		TTT	7,0	9/27/22	21	272
200-		TTT	7,7	137	39	233
202-	FC		6,3	26/31	22	277
202-	FC		6,3	34/39	19	271
202-		TTT	6,5	113	31	242
204-	FC		5,5	29/5	17	298
204-	FC		5,9	25/20	21	288
204-	FC		5,9	45/48	20	267
204-		TTT	5,5	62/6/62	21	259
204-		TTT	6,6	138	32	240

As seen, the dent depth has minor influence on the residual strength. However, the damage extent, which particular laminate experienced during impact and fatigue loading, is more important. The higher degree of damage was induced to the laminate, the less its residual strength was achieved. Therefore, most reduction in the laminate residual strength would be due the through-the-thickness type of impact damage. This is clearly seen, based on the residual strength results of 200 specimen group.

An empirical method was used in order to predict the residual strength of dented GLARE with TTT type of damage [9]. This method is based on calculation of the residual strength of laminates with sharp through the-thickness notches. The metal and fiber volume fracture in the laminate loading direction as well as K_R-curve for 2024-T3, to obtain the laminate one, are main parameters used in the method. For calculations, dent TTT damage was represented by an average through-the-thickness crack length based on fatigue cracks measured on both sides of the laminate. The output of the residual strength calculations is presented in Fig. 8 together with the experimental data.

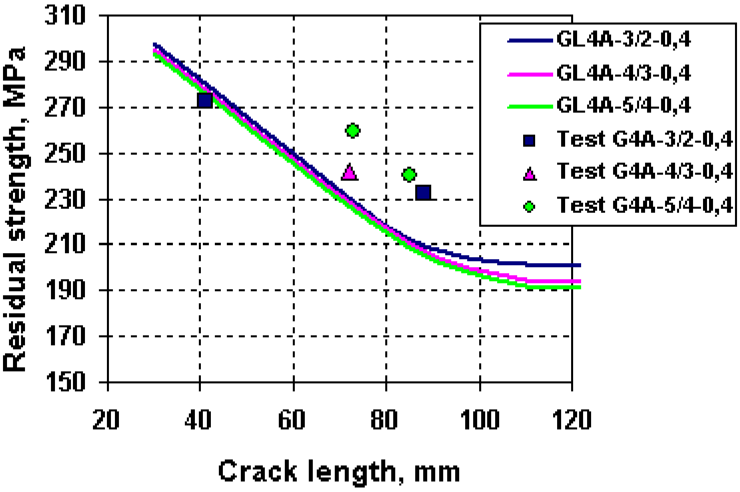


Figure 8: Comparison of predicted and experimental values of residual strength.

As seen, the method gives conservative predictions. As mentioned above, in the method the damage is represented as a through-the-thickness crack. This means that all aluminium and fiber prepreg layers are being cut through, whereas in the case of dent TTT damage not all fibers in the loading direction are considered as broken. Since the residual strength of fiber metal laminates is partially depends on the amount of intact fibers to carry load in the loading direction, this explains why the predicted residual strength values are lower than the experimental ones.

4. CONCLUSIONS

In general, GLARE® showed excellent resistance to dynamic impact and fatigue loading. There was linear relationship between the dent depth and impact energy for all investigated laminates. However, for the same dent depth larger delaminations were founded in the thickest laminate in comparison with the ones detected in thinner laminates. The growth of induced impact delaminations was rather limited when the laminates were tested in fatigue. The measured delamination increase was due to the effect of fiber bridging followed the metal crack propagation under cyclic loading. If impact cracks were induced on the non-impacted side of laminates, they did not propagate in fatigue. The residual strength of impacted GLARE® with through-the-thickness type of dent damage could be conservatively predicted based on calculation of the residual strength of laminates with through-the-thickness notches.

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