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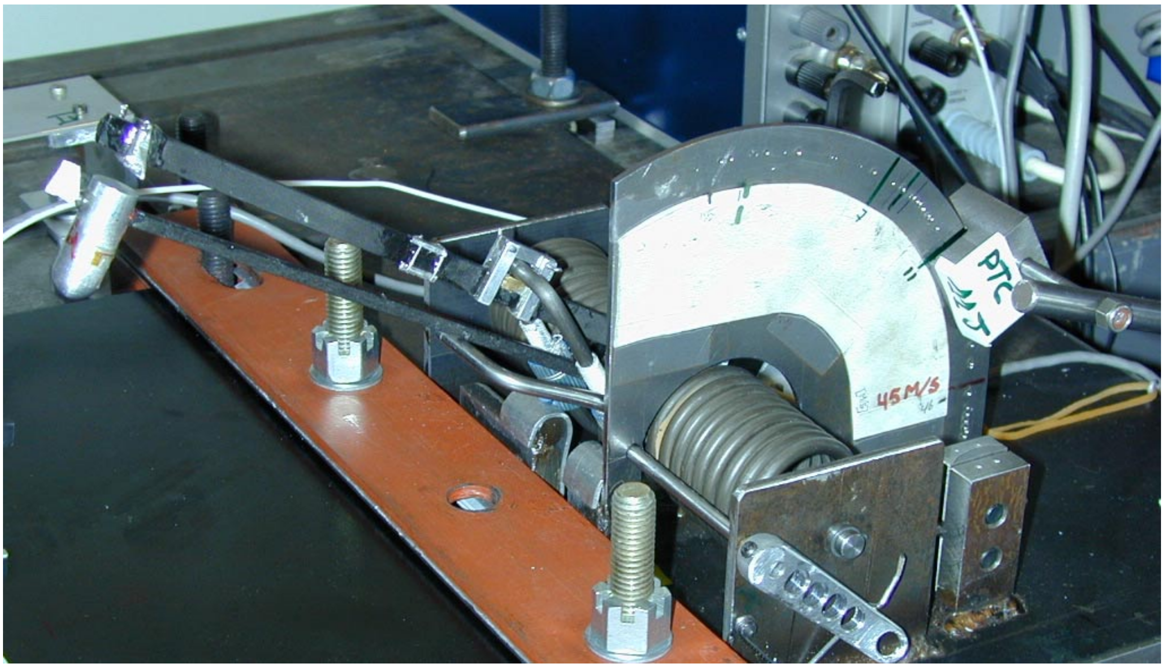
Robin Olsson and Christophe Paget

Response and damage due to medium velocity impact on composites



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Response and damage due to medium velocity impact on composites

Abstract (not more than 200 words)

This report describes response and damage of carbon fibre/epoxy composite laminates under medium velocity impact tests. A quasi-isotropic and a wing relevant 3 mm thick layup were tested for each of the materials IM7/8552 and IM7/977-2. Tests were done with an instrumented 10 g impactor at 37 and 47 m/s (7J and 11J). Impact response is expressed by contact load and deflection histories. Damage is quantified by dent depth and size of the delamination zone. The results demonstrate that runway debris may cause significant delaminations without any visible surface damage. Except for a given material and lay-up there was no direct correlation between dent depth and delamination size. Actually, the most severe delaminations were found in the material with the smallest dents.

Keywords
Composite materials, Impact, Impact damage, Impact loads

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Rapportens titel (i översättning)
Respons och skador hos kompositer vid slag med medelhög hastighet

Sammanfattning (högst 200 ord)

Denna rapport beskriver respons och skador i kompositlaminat av kolfiber/epoxi vid slagprov med medelhög hastighet. En kvasiisotrop och en vingrelevant 3 mm tjock uppläggning provades för vart och ett av materialen IM7/8552 och IM7/977-2. Prov utfördes med en instrumenterad 10 g slagkropp vid 37 och 47 m/s (7J and 11J). Slagresponsen presenteras form av kontaktlast och utböjningshistorier. Skadorna kvantifieras genom intryckningsdjup och storlek på delamineringsområdet. Resultaten visas att stenskott kan orsaka betydande delamineringar utan någon synlig skada på ytan. Förutom jämförelser för ett givet material och en given uppläggning fanns ingen direkt koppling mellan intryckningsdjup och delamineringsstorlek. I själva verket upptäcktes de största delamineringarna i materialet med de minsta intryckningarna.

Nyckelord
Kompositmaterial, slag, slagskador, slagbelastning, intryckning, dubbelskalspaneler

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Contents

Executive summary

Impact damage is a major consideration for laminated composite structures, since it may severely reduce the strength and stability of the structure. Typical impact threats are dropped tools, runway debris and hail.

The impact resistance of composites is conventionally measured in low velocity drop weight tests. However, the deflection shape in drop tests is normally similar to that under static loading, which is strongly influenced by specimen geometry and boundary conditions. Properly designed drop tests may be a good measure of the effect of dropped tools but cannot simulate the response to medium velocity runway debris and hail, which cause a more local response unaffected by boundary conditions. As a result of the more local energy absorption small mass impactors normally cause higher loads and more extensive damage for a given impact energy.

This report describes the response and damage of composite laminates under impact by simulated hail or runway debris. Tests were done with a unique instrumented impact apparatus of a design similar to a large mouse trap. Two carbon fibre/epoxy materials, each with a quasi-isotropic and a wing relevant lay-up, were tested with an instrumented 10 g impactor at 37 and 47 m/s corresponding to energies of 7 J and 11 J. The dynamic response is expressed in terms of contact force and deflection histories. The resulting damage is expressed in terms of dent depth and delamination size.

In contrast to large mass impacts, load and deflection were out-of-phase, as expected from theory for small mass impact. The response histories for a given impact velocity were highly repeatable, independent of impact position, and did not show any significant differences for different lay-ups or materials.

The delamination areas increased with impact energy and were similar for both lay-ups, although the shape was more extended in the wing relevant lay-up. The resulting dents were non-visible or barely visible. Material and lay-up influenced the dent depth, but there was no direct relation between visibility and delamination size. In fact, the material with the smallest dents suffered the largest delaminations. This indicates that tough plastic matrices are beneficial both in reducing delamination size and in increasing damage visibility.

It is suggested that visibility should be ruled out as measure of damage severity. Tests of strength and fatigue after impact should be made to compare the effect of large and small mass impact. In such tests it is important that the large mass impact tests are done on specimens with geometry and boundary conditions representative of the real structure. Furthermore, a judicious selection should be made of the large and small mass impacts to be compared. Possible approaches include equal impact energy, equal visibility or equal risk. All approaches require definition of additional parameters, such as impactor mass, shape and velocity, which may all strongly influence the results.

1. Introduction

Impact damage is a major consideration for laminated composite structures, since it may severely reduce the strength and stability of the structure. Typical impact threats are dropped tools, runway debris and hail.

The resistance to impact threats is frequently measured at a given impact energy in conventional drop weight tests with large mass impactors. Such tests normally result in a quasi-static response, where the impact energy is absorbed by deflections in the entire specimen. Drop tests are strongly influenced by specimen geometry and boundary conditions, but properly designed specimens may provide a good measure of the effect of dropped tools.

However, drop tests cannot simulate impact by small mass medium velocity impactors, such as hail or runway debris, which cause a more local response governed by transient flexural waves. The response in small mass impacts is unaffected by edge conditions and generally results in higher loads and more severe damage [1-2].

This report describes small mass impact tests on composite laminates, performed with an instrumented 10 g impactor at energies of 7 J and 11 J. These experiments simulate the medium velocity impact by hail or runway debris.

2. Impact equipment and specimens

2.1 Impact apparatus

The impact apparatus is based on an instrumented small mass impactor on a pendulum arm, which is actuated by a spring of the same design as in a large mouse trap, Figures 1 and 2. The apparatus was developed at FFA and the basic design is described in [3]. In the present work the apparatus was extensively modified to overcome a number of problems encountered during the initial tests.

2.2 Impactor

The impactor consists of a 10.2 g high grade (E=70.6 GPa) aluminium cylinder with a 6.35 mm radius hemispherical tup, Figure 1. Previous dynamic FE simulations have verified that the flexible 2 g impactor arm does not affect the primary impact event.

2.3 Specimen supports

The specimen supports consisted of two parallel steel beams, which provide simply supported conditions along the longer sides and unsupported conditions along the shorter edges, Figures 1 and 2. The distance between the supports was 220 mm. Initial calculations, based on the expressions in [1], indicated that a distance of 90 mm to an edge or neighbouring impact damage would be sufficient to ovoid interaction completely, while a distance of 60 mm would be sufficient to avoid interaction during most of the impact. The lack of interaction with edges was validated by comparing response and damage for mid-bay impact 200 and 100 mm from the free edges.

2.4 Specimens

Specimens were manufactured by QinetiQ using two different carbon fibre/epoxy systems, IM7/8552 and IM7/977-2. Both materials were tested with a $[\pm45/0/90]_{3S}$ quasi-isotropic layup (QI) and a $[90/0/\mp45/90/\mp45/90/0/\mp45/90]_{s}$ wing relevant layup (WR), where the 0°-direction coincides with the longer side of the panel. Each panel type was impacted at an energy of 7 J and 11 J. The panels had a size of 3.1x250x500 mm and an areal weight of 4.9 kg/m^2 and were all impacted at four locations with 100 mm distance. Each panel was given an identification code, which describes material, layup and number. Table 1 gives a translation to the corresponding QinetiQ manufacturing numbers.

3. Measurements and measuring equipment

3.1 Impact velocity

The impact velocity (37-47 m/s) was measured by letting a flag on the impactor pass two slotted optical switches (Optek OPB815W) mounted on the long L-shaped bar in the left of Figure 1. The switches, which start and stop a digital clock (FFA 2397), were placed with a distance of 40.1 mm. The standard deviation of the impact velocities dig not exceed 1 %, Tables 2 and 3.

3.2 Impact load

The impact load was measured by a pair of strain gauges (Kyowa KFG-2-120-C1-11L3M3R). The signal was amplified 500x in a bridge amplifier (FFA 1202X), modified for 150 kHz band width, Figure 3. The gauge factor (4.01 kN/V) was obtained from the statically calibrated signal (2.5 kN/V) multiplied by a dynamic factor (1.604), to account for differences in the tup load under an inertial volume load and a static end load [4].

3.3 Plate deflection

The plate deflection during impact was measured with a laser displacement sensor (Latronix) on the lower face of the plate. The sensor appears as a black box in Figure 2 and has a band width of approximately 100 kHz. It has a gauge factor of 0.4529 mm/V and a range of –1 to +6 mm when placed 51 mm from a white sticker on the target.

3.4 Transient data acquisition

Data acquisition was obtained with a 400 MHz four channel digital memory oscilloscope (LeCroy 9314CM), Figure 3. A microphone located close to the impact point was used for external triggering since noise in the load signal caused triggering problems. After each impact the data was dumped on a Macintosh Quadra 900 computer and evaluated using LabView™ 4.0.1 software from National Instruments.

3.5 Dent depth

The dent depth after impact was measured by moving the impacted laminate horizontally on a frame located under a fixed laser displacement sensor (MEL M5L/20) which measured the distance of the plate at an accuracy of less than ±0.06 mm, Figure 4. The dent depth was defined as the difference between the distance to the impact centre and the average distance to four points at 25 mm radius from the impact centre. All measurements of the dent depth were done less than 15 minutes after the impact to avoid relaxation spring back observed in some previous studies.

3.6 Delamination size

The delamination size after impact was measured with ultrasonic C-scan to validate repeatability and non-interference with neighbouring impacts. For each test case delaminations at different sites were fairly similar and did not indicate any influence of location or of previous impacts. Delamination length and width were defined to agree with the length and width directions of the intended coupons for subsequent residual strength tests, Figure 5.

4. Test procedure

The test sequence was designed to secure repeatability and that damage and response were unaffected by edges or neighbouring impacts. Each panel was impacted at four locations (A to D), Fig. 5, where the impact energy was alternated between 7 J and 11 J to minimise influence of large delaminations. For each laminate type and energy the response and delamination size for central impacts (locations B and C) was compared with end impacts (locations A and D). Some additional recordings were then made to study response and damage in presence of previous neighbouring impact damage. In all cases the results were highly repeatable and without any signs of influence of impact location or neighbouring damage. Thus, only two to three recordings were made for each of the remaining test cases. An overview of all tests is given in Tables 2 to 3 and Figure 6, where instrumented tests are shown in bold letters.

5. Results and discussion

5.1 Impact histories

The impact load histories consist of a strongly oscillating load, where the mean value quickly reaches a plateau value and then gradually decays to zero, Figures 7 to 14. The deflection increases proportionally to the impulse (load-time integral) and reaches a plateau value at the end of impact, as expected from theory [2]. An FFT-analysis revealed that the period of the high frequency oscillation was about 13 μs at both impact velocities, although the amplitude is significantly larger at the higher velocity. The oscillation period agrees almost exactly with the expected return time for longitudinal waves in the impactor, which seem to be the most likely cause for these oscillations.

For equal impact conditions a high degree of repeatability is observed in the impact response. The deviating deflection for case 8552WR2C at 7J does not seem to be a result of damage formation, since the deflection is much larger than observed at the higher energy. A possible cause might be failure of the white sticker on the laminate back face. For each impact velocity both lay-ups have a very similar response, which is to be expected since load and deflection is governed by the average flexural stiffness of all directions in the plate [1-2]. The load histories at a given velocity do not differ significantly between the two material systems. However, the deflections are larger for the IM7/8552 material than for IM7/977-2, which is in agreement with the smaller delaminations observed in the latter material.

5.2 Dent depths

Dent depths after impact were typically 0.4 to 0.6 mm and hardly visible. The dent depth showed a larger scatter for the lower impact velocity, Tables 2 and 3. Single abnormal values, shown within brackets in the tables, have been discarded when calculating mean dent depths. The abnormal values may be a result of surface imperfections prior to testing. Figure 15 gives a comparison of mean dent depths for the different test cases. The higher impact energy caused an increased dent, except for the 977-2 quasi-isotropic lay-up, where the weak opposite trend is unexpected but probably not significant. The dent depth was generally larger for the quasi-isotropic layup than for the wing relevant layup. The dent depth was also somewhat larger for the 977-2 matrix, which indicates larger plastic deformations.

5.3 Delamination sizes

Delamination zone sizes obtained from ultrasonic C-scan are listed in Tables 2 and 3. Here, width and length coincide with the width and length directions of the coupons to be cut out for residual strength tests. The delamination zone in quasi-isotropic laminates is almost circular, although the individual delaminations in each interface are peanut shaped. The delamination zone in the wing relevant layup is elliptical with an aspect ratio of 1.15 to 1.25, where the major axis coincides with the direction of higher stiffness.

Figure 16 gives a comparison of mean delamination zone diameters, defined as the geometric average of the length and width of the delamination zone. It is noted that the average delamination zone diameter (and thus delamination area) is independent of layup. The size of the delamination zone increases with impact energy, as expected. Finally, the size of the delamination zone was somewhat smaller for the 977-2 matrix, which indicates a higher interlaminar toughness.

6. Conclusions

Instrumented tests with small mass impactors, representative of hail or runway debris, have been shown to result in significant damage at fairly low impact energies (7 and 11 J). As a result of the response type, damage is independent of boundary conditions and can not be reduced by modifying panel geometry or boundary conditions. The resulting dents are non-visible or barely visible. In fact, the material with the smallest dents suffered the largest delaminations. This indicates that tough plastic matrices are beneficial both in reducing delamination size and in increasing damage visibility. Note that, except for a given material and lay-up, there is *no direct relation between damage visibility and delamination size.* However, a visible dent is in most cases an indication of significant damage. The delamination zone is generally less extended in the laminate direction with lower stiffness, which normally is perpendicular to the principal load direction. This may be beneficial in cases where damage may be approximated as a notch. However, the influence on delamination stability and growth is less evident.

7. Recommendations

In agreement with several previous studies the present results strongly suggest that visibility should be ruled out as a measure of damage size. The observed correlation between small damage and large dents (good visibility) should be considered in future studies and material development.

Tests of strength and fatigue after impact should be made to compare the influence of small and large impactor masses. In large mass impact tests it is important that the specimen geometry and boundary conditions are representative of the real structure. In contrast, small mass impact tests can be done on fairly small specimens with arbitrary boundary conditions. Residual strength tests should ideally be representative of the real structure, at least in compression, where buckling may be a significant failure mode.

A logical and judicious definition is required of the small and large mass impact cases to be compared, since different approaches are possible. A conventional “certification approach” based on equal impact energy requires definition of impactor masses and shapes representative of realistic threats, since these factors influence damage size and visibility. An “inspection approach” based on equal visibility requires definition of impactor shape and a fixed laminate material and layup, since these factors strongly influence visibility. A “risk approach” based on impact cases of equal risk requires that the risk of different impact threats has been quantified. Furthermore, it should be noted that the parts and load conditions of the structure exposed to small mass impact may differ from those exposed to large mass impact.

8. Acknowledgements

This research was commissioned and monitored by Toby Turton, Phil Best and Emile Greenhalgh at the Structures and Materials Centre at QinetiQ, UK. The research was funded by the UK MoD under the research package 5. “Control and Denial of Theatre Airspace” manged by Mr. G. Wickham.

Torvald Linderoth and Kjell Welin did a great job at repairing and improving the impact apparatus.

9. References

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2. Olsson, R. (1992) Impact response of orthotropic composite plates predicted from a one-parameter differential equation, *AIAA Journal*, Vol 30, No 6, pp 1587-1596.
3. Beks, F.-A. (1996) Examination of impact response and damage of composite laminates, *FFA TN 1996-29*, The Aeronautical Research Inst. of Sweden, Bromma.
4. Jarlås, R.; Olsson, R. (1997) Analysis of equipment used for small mass impact experiments, *FFAP H-1291*, The Aeronautical Research Inst. of Sweden, Bromma.

Tables

Table 1 Translation of panel numbers

FFA designation	QinetiQ designation
8552QI1	B0224A
8552QI2	B0221B
8552QI3	B0221A
8552WR1	B0210B
8552WR2	B0178A
8552WR3	B0177A
977QI1	A0347B
977QI2	A0347A
977QI3	A0345A
977WR1	B0241A
977WR2	B0240A
977WR3	B0240B

Table 2 Test results for material 8552

Material	Panel	Nominal energy [J]	Velocity [m/s]	Impact energy [J]	Dent depth [mm]	Delam. width [mm]	Delam. length [mm]
8552	**QI1B**	7	38.0	7.22	(0.910)	22	25
8552	**QI1D**	7	38.0	7.22	0.397	23	23
8552	**QI2A**	7	38.0	7.22	0.570	28	29
8552	**QI2C**	7	38.0	7.22	0.400	27	27
8552	QI3A	7	38.0	7.22	0.395	27	28
8552	QI3C	7	38.0	7.22	0.297	24	25
8552	*QI*	*7*	*38.0±0%*	*7.22±0%*	*0.41±24%*	*25±10%*	*26±9%*
8552	WR1B	7	38.7	7.49	0.163	23	25
8552	WR1D	7	38.7	7.49	0.255	22	27
8552	**WR2A**	7	38.0	7.22	0.273	29	35
8552	**WR2C**	7	38.0	7.22	0.153	22	30
8552	WR3A	7	38.0	7.22	0.245	21	30
8552	**WR3C**	7	38.0	7.22	(0.088)	25	32
8552	*WR*	*7*	*38.2±1%*	*7.31±2%*	*0.22±26%*	*24±12%*	*30±12%*
8552	QI1A	11	46.7	10.9	0.625	34	34
8552	**QI1C**	11	47.0	11.0	0.465	32	32
8552	**QI2B**	11	47.0	11.0	0.587	37	34
8552	**QI2D**	11	47.0	11.0	0.572	31	32
8552	QI3B	11	46.8	10.9	0.540	33	37
8552	QI3D	11	47.0	11.0	0.522	31	34
8552	*QI*	*11*	*46.9±0%*	*11.0±0%*	*0.55±10%*	*33±7%*	*34±5%*
8552	WR1A	11	47.0	11.0	0.500	33	38
8552	**WR1C**	11	47.0	11.0	0.415	31	41
8552	WR2B	11	47.0	11.0	0.572	34	36
8552	WR2D	11	46.7	10.9	0.402	32	35
8552	**WR3B**	11	46.8	10.9	0.407	34	36
8552	**WR3D**	11	46.9	11.0	0.382	36	41
8552	*WR*	*11*	*46.9±0%*	*11.0±0%*	*0.45±17%*	*33±5%*	*38±7%*

Tests in **bold** letters were instrumented Data in brackets neglected for mean values
Data in *italics* show mean values with standard deviation in percent

Table 3 Test results for material 977-2

Material	Panel	Nominal energy [J]	Velocity [m/s]	Impact energy [J]	Dent depth [mm]	Delam. width [mm]	Delam. length [mm]
977-2	**QI1B**	7	37.1	6.88	0.687	22	22
977-2	**QI1D**	7	37.1	6.88	0.580	21	21
977-2	QI2A	7	37.2	6.92	0.632	22	20
977-2	QI2C	7	37.2	6.92	0.765	23	20
977-2	QI3A	7	37.2	6.92	(0.937)	20	20
977-2	QI3C	7	37.2	6.92	0.615	20	19
977-2	*QI*	*7*	*37.2±0%*	*6.91±0%*	*0.66±11%*	*21±6%*	*20±5%*
977-2	**WR1B**	7	37.4	6.99	0.480	24	25
977-2	**WR1D**	7	37.3	6.96	0.540	23	25
977-2	WR2A	7	37.3	6.96	0.352	23	24
977-2	WR2C	7	37.3	6.96	0.405	19	22
977-2	WR3A	7	37.4	6.99	0.547	17	21
977-2	**WR3C**	7	37.3	6.96	0.497	17	23
977-2	*WR*	*7*	*37.3±0%*	*6.96±0%*	*0.47±16%*	*20±16%*	*23±7%*
977-2	**QI1A**	11	47.0	11.0	0.602	27	28
977-2	**QI1C**	11	47.1	11.1	0.667	28	27
977-2	QI2B	11	47.1	11.1	0.652	27	27
977-2	QI2D	11	47.0	11.0	0.642	23	24
977-2	QI3B	11	46.7	10.9	0.607	27	28
977-2	QI3D	11	46.6	10.9	0.672	25	27
977-2	*QI*	*11*	*46.9±0%*	*11.0±0%*	*0.64±5%*	*26±7%*	*27±5%*
977-2	WR1A	11	46.9	11.0	0.490	24	30
977-2	**WR1C**	11	46.9	11.0	0.590	24	29
977-2	**WR2B**	11	46.9	11.0	0.597	27	29
977-2	**WR2D**	11	46.9	11.0	0.535	30	32
977-2	WR3B	11	46.9	11.0	0.512	27	29
977-2	WR3D	11	46.9	11.0	0.632	26	31
977-2	*WR*	*11*	*46.9±0%*	*11.0±0%*	*0.56±10%*	*26±9%*	*30±4%*

Tests in **bold** letters were instrumented Data in brackets neglected for mean values
Data in *italics* show mean values with standard deviation in percent

Figures

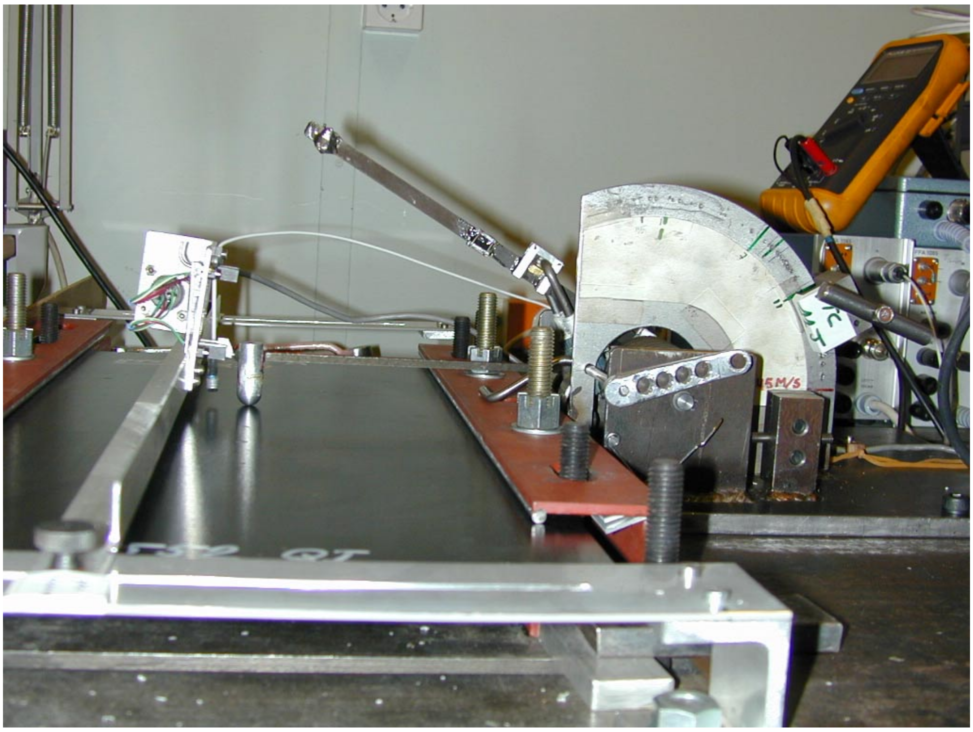

Figure 1 Impact apparatus with impactor resting on impacted laminate

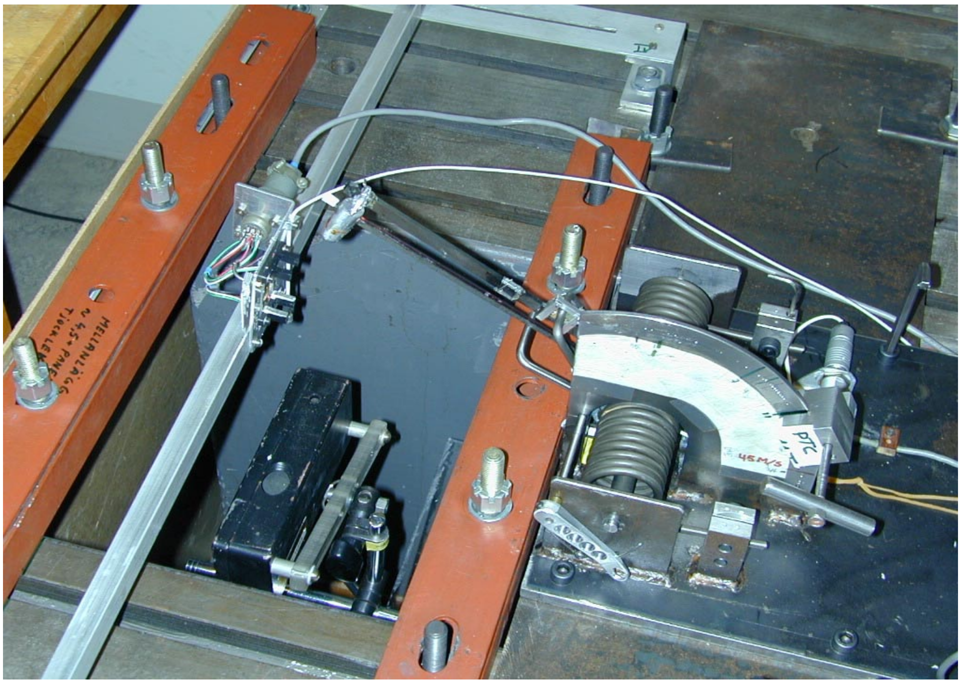

Figure 2 Impact apparatus with impacted laminate dismounted

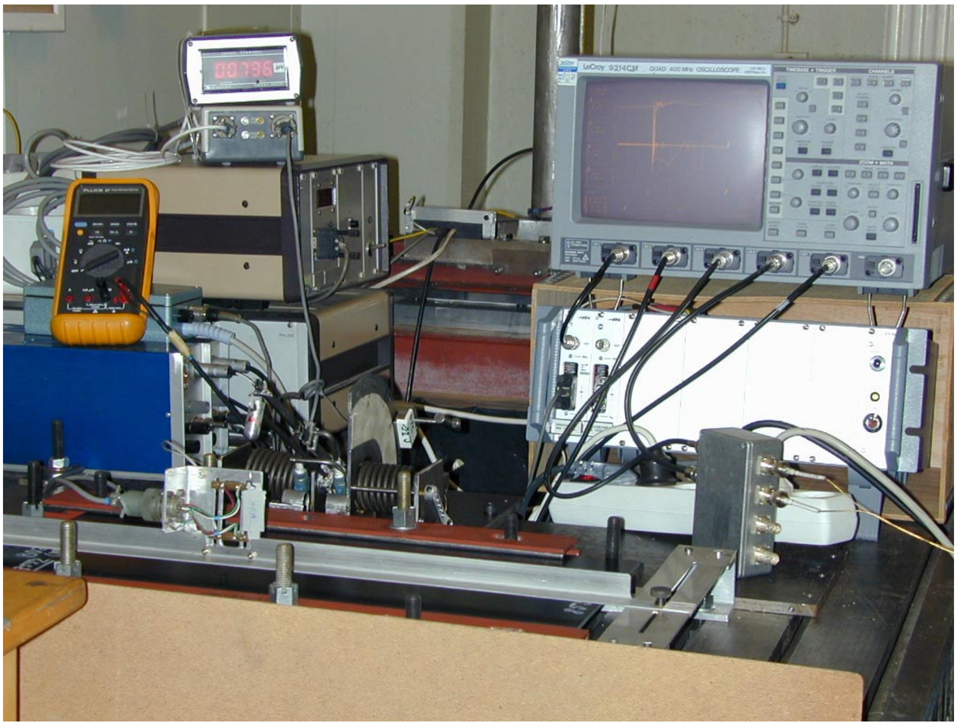

Figure 3 Experimental set-up with recording equipment

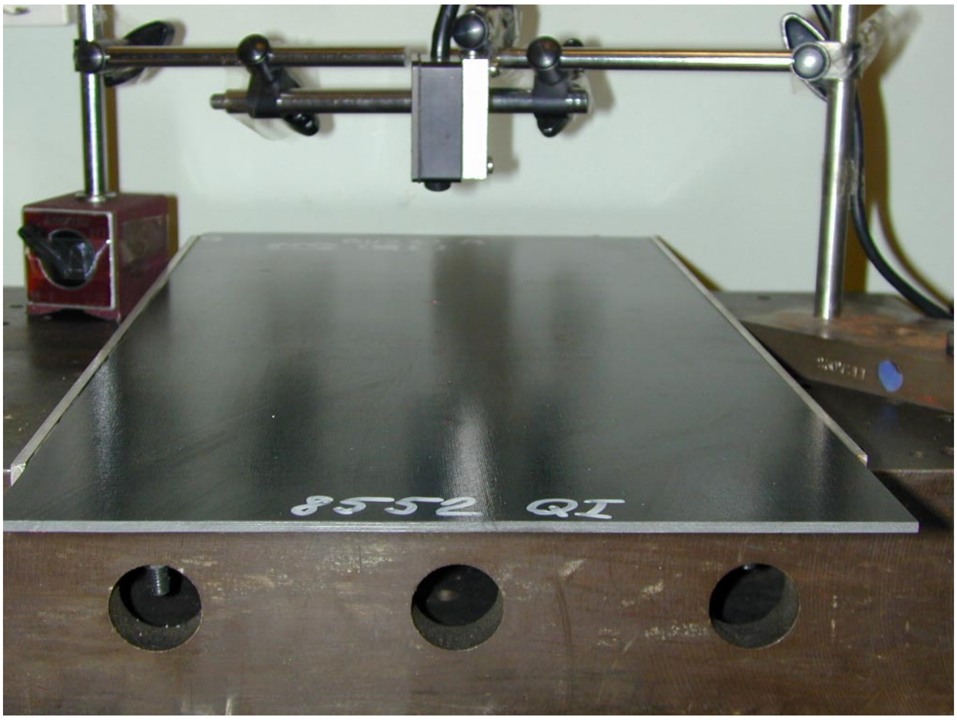

Figure 4 Set-up for measurement of dent depth

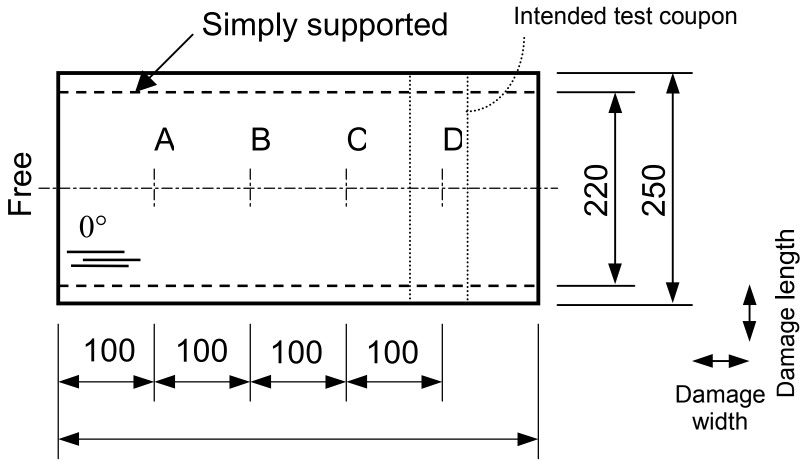

Figure 5 Geometry and test positions of panels

Material and layup type

Panel Nr.	8552QI					8552WR			
	11J	7J	11J	7J		11J	7J	11J	7J
1	A	**B**	**C**	**D**		A	B	**C**	D
	21	1	22	5		23	2	24	6
	7J	11J	7J	11J		7J	11J	7J	11J
2	**A**	**B**	**C**	**D**		**A**	B	**C**	D
	9	3	10	7		11	4	12	8
	7J	11J	7J	11J	Energy	7J	11J	7J	11J
3	A	B	C	D	Location	A	**B**	**C**	**D**
	13	19	14	20	Test nr.	15	17	16	18

Nr.	977QI					977WR			
	11J	7J	11J	7J		11J	7J	11J	7J
1	**A**	**B**	**C**	**D**		A	**B**	**C**	**D**
	21	1	22	5		23	2	24	6
	7J	11J	7J	11J		7J	11J	7J	11J
2	A	B	C	D		A	**B**	C	**D**
	9	3	10	7		11	4	12	8
	7J	11J	7J	11J	Energy	7J	11J	7J	11J
3	A	B	C	D	Location	A	B	**C**	D
	13	19	14	20	Test nr.	15	17	16	18

(instrumented tests in bold letters)

Figure 6 Energies, test positions and test nr. for each panel

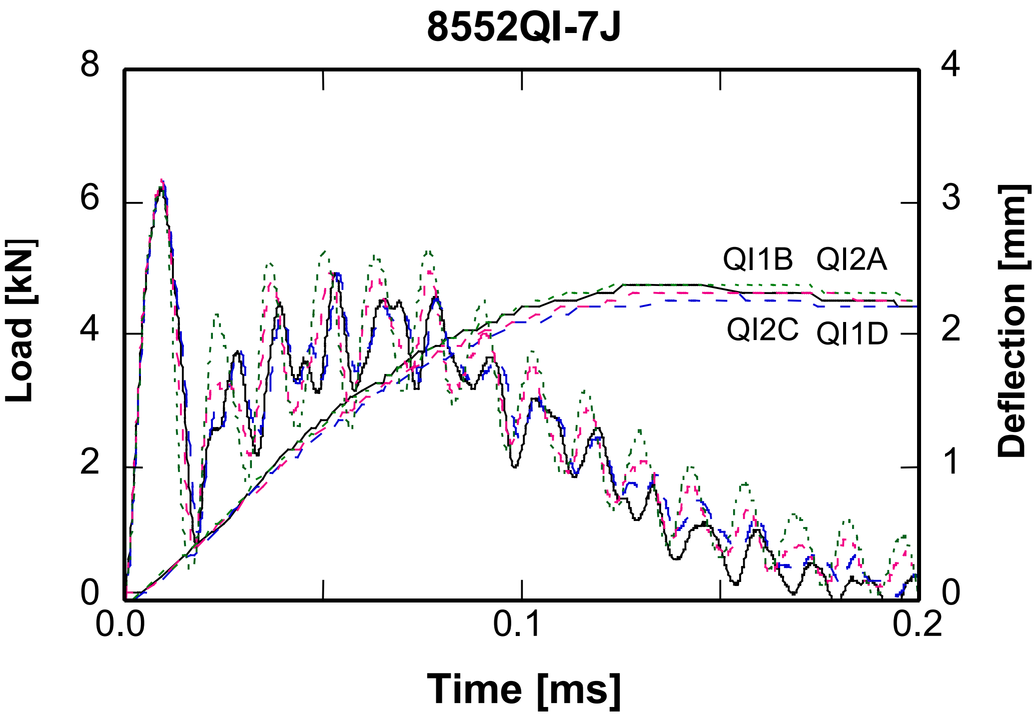

Figure 7 Impact response of four 8552QI panels at 7J

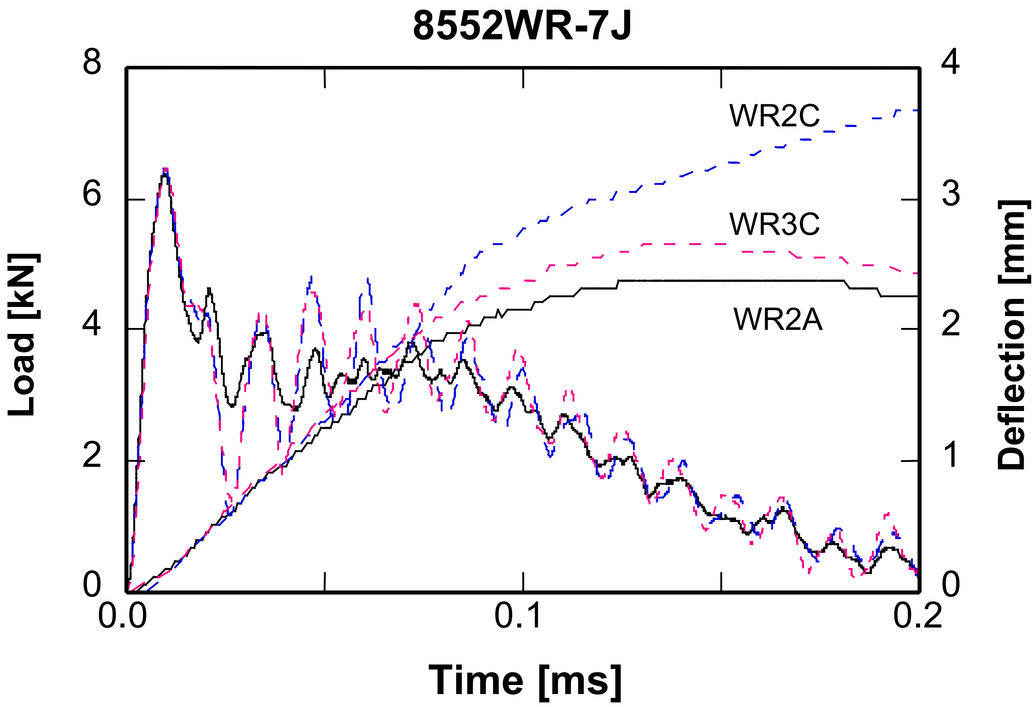

Figure 8 Impact response of three 8552WR panels at 7J

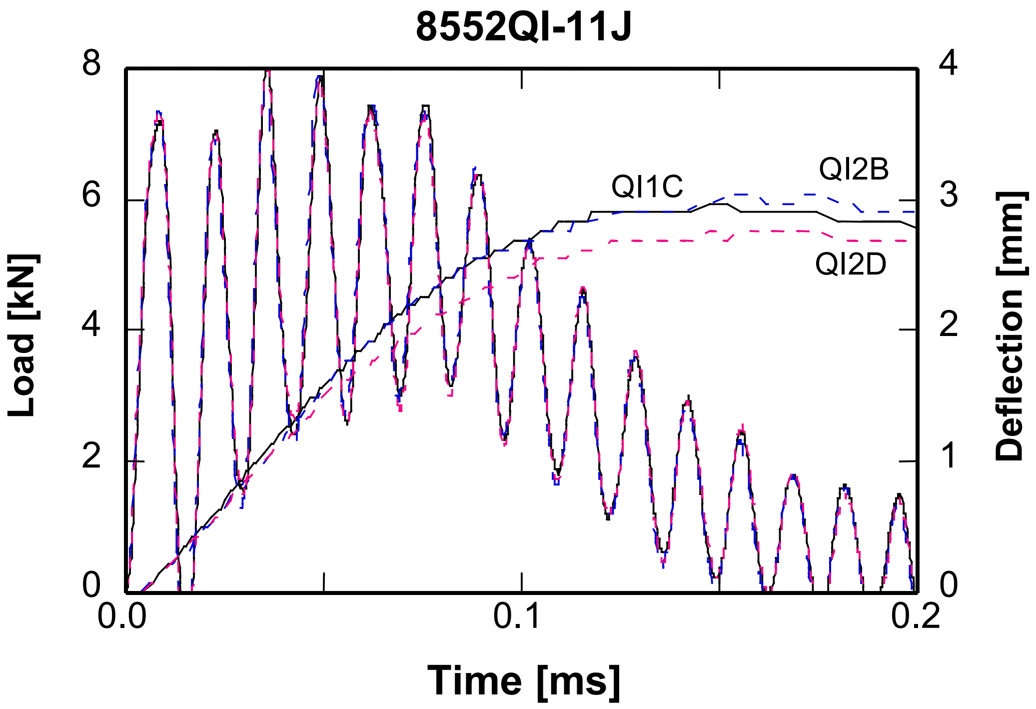

Figure 9 Impact response of three 8552QI panels at 11J

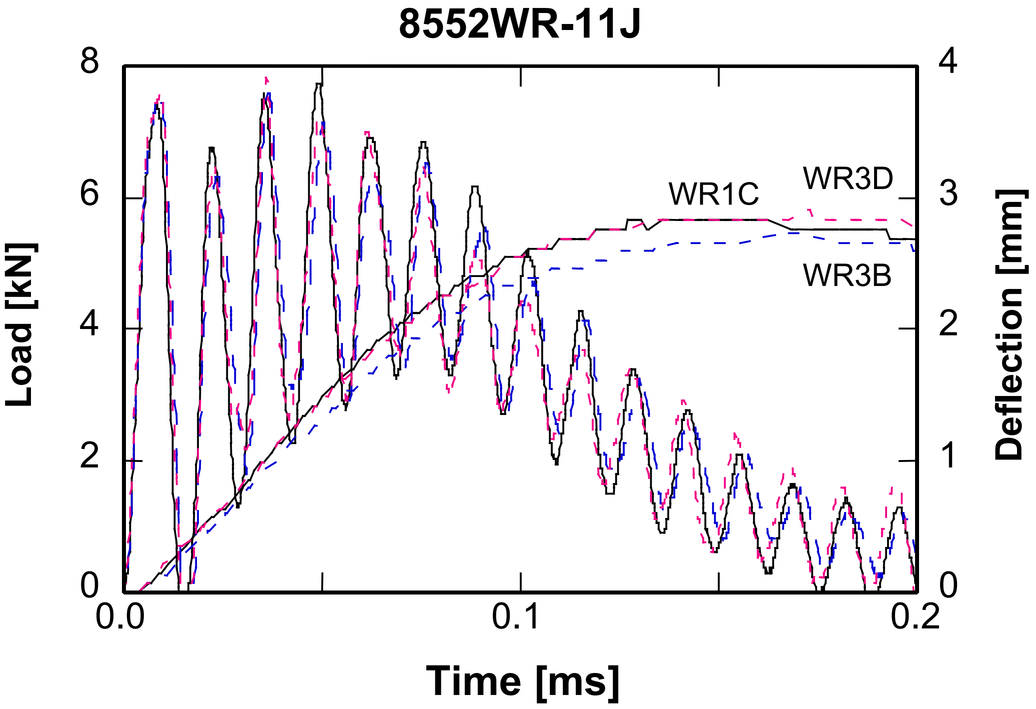

Figure 10 Impact response of three 8552WR panels at 11J

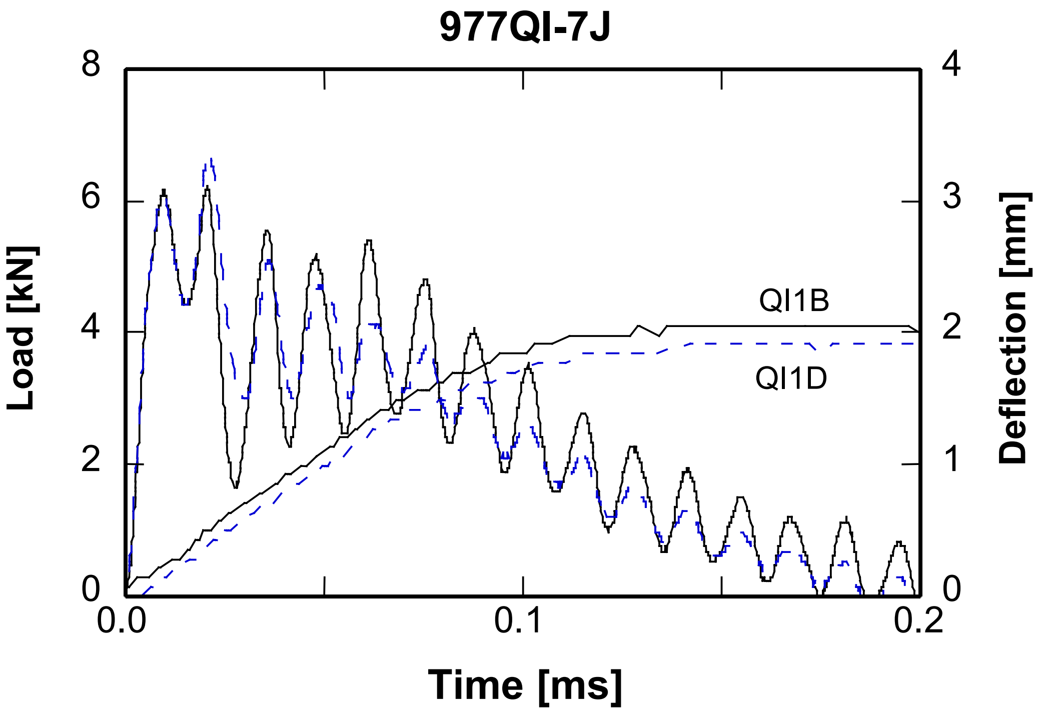

Figure 11 Impact response of three 977QI panels at 7J

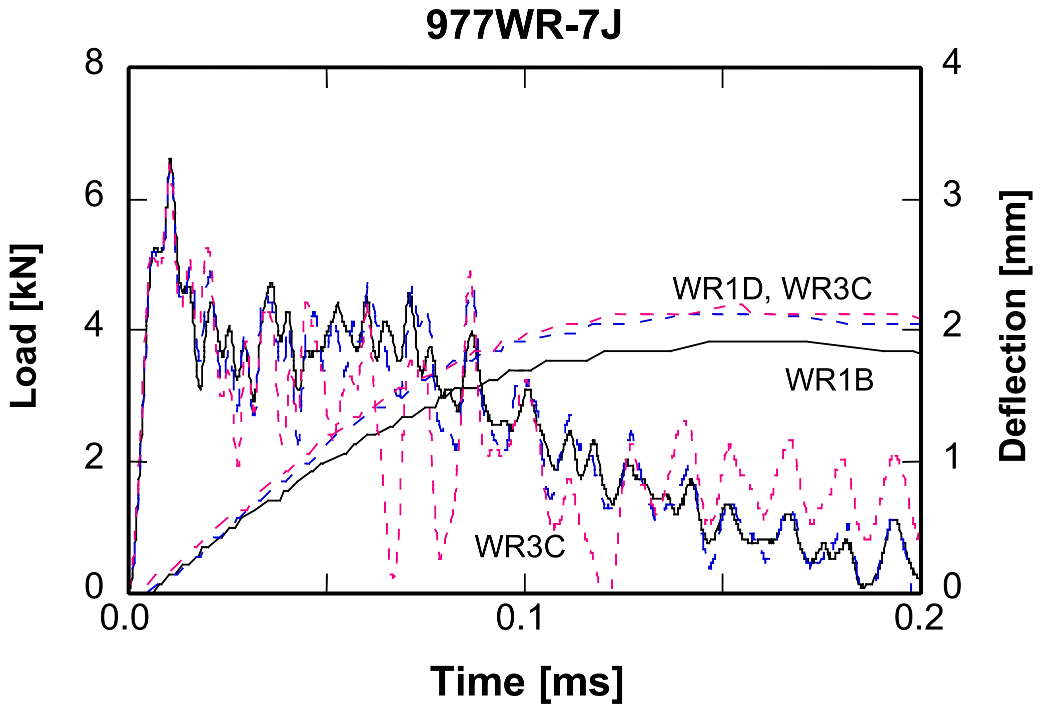

Figure 12 Impact response of three 977WR panels at 7J

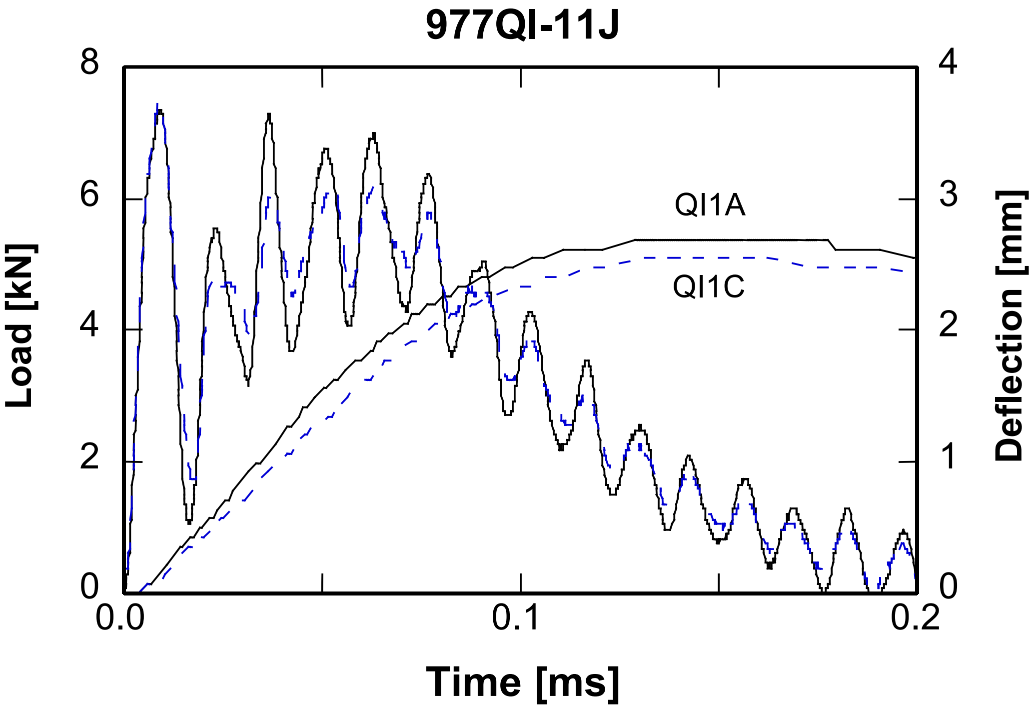

Figure 13 Impact response of two 977QI panels at 11J

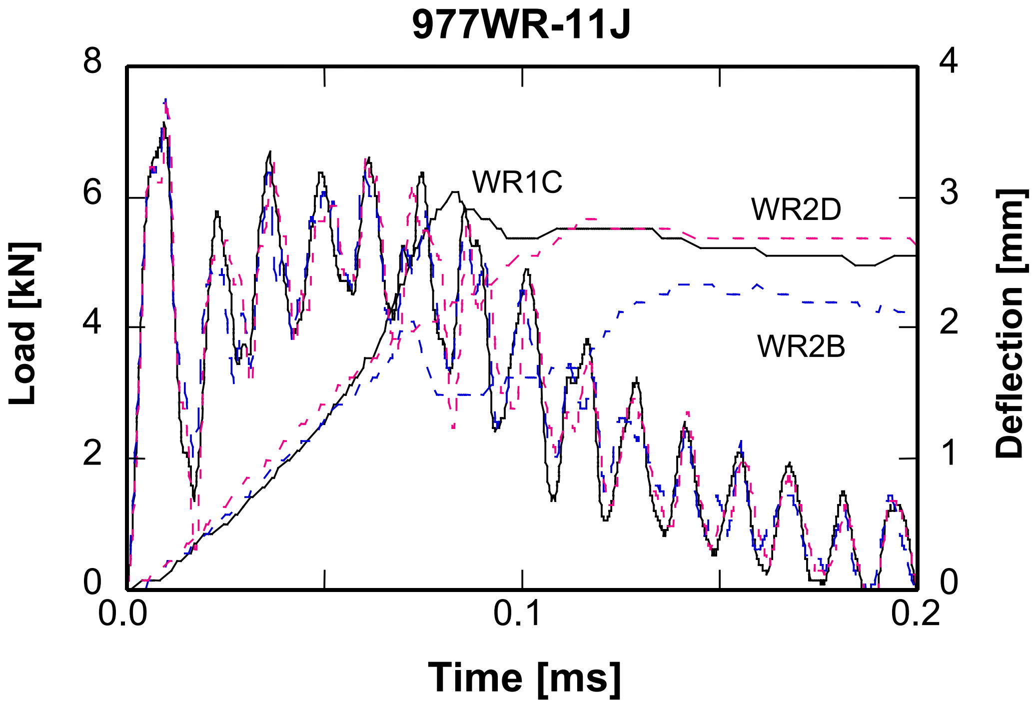

Figure 14 Impact response of three 977WR panels at 11J

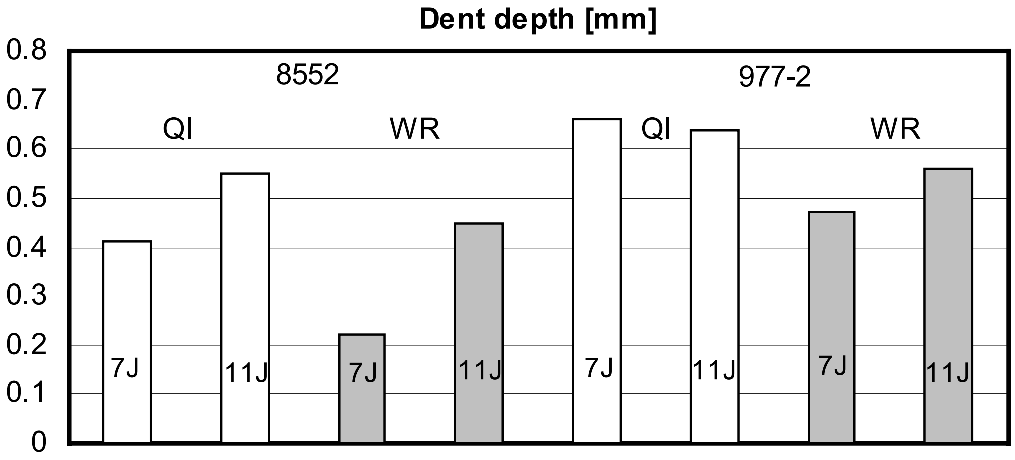

Figure 15 Comparison of average dent depths

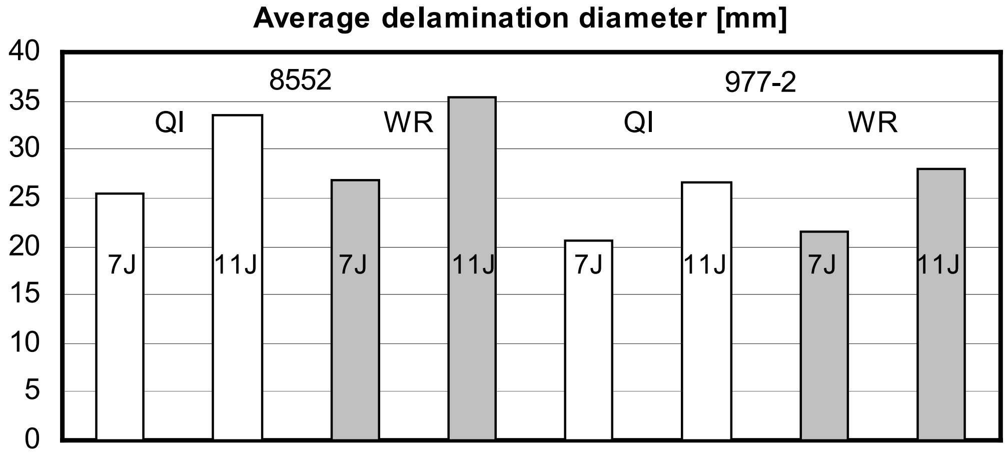

Figure 16 Comparison of average delamination diameters