Experimental observations of damage propagation in open hole tension specimens

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Basic Research Grants Scheme 2002

A Study of Damage Initiation and Growth in Composite Bolted Joints

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Experimental Observations of Damage Propagation in Open Hole Tension Specimens

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Section 1: Introduction

The project “A Study of Damage Initiation and Growth in Composite Bolted Joints” is funded under the Basic Research Grants Scheme 2002, jointly administered by Enterprise Ireland and the Irish Research Council for Science, Engineering and Technology. It runs from October 2002 to March 2006.

The goal of the project is to develop computational models for prediction of the initiation and growth of damage in composite bolted joints. Two approaches are being investigated. The first is based on a stiffness reduction scheme. The second is based on continuum damage mechanics. Experimental data is also being generated to provide the parameters for the models and to validate their predictions.

The present report (deliverable D3.3) discusses experimental observations from tests in which open-hole tension specimens were loaded to varying percentages of their ultimate failure load. The progression of damage with increasing load is thus revealed. Results for tests to failure have already been presented in Deliverable D3.2, ‘*Report on Material Calibration Tests, Open-Hole Tension Tests and Filled Hole Tests*’ [1]. The tests in the present report involve two material systems, HTA 6376 carbon fibre reinforced plastic (CFRP) and S2 FM 94 glass fibre reinforced plastic (GFRP). Both material systems are commonly used in structural applications in the aerospace industry. A variety of laminate lay-ups and configurations are examined. Damage progression observed in the tests is used to explain the different failure modes and strengths of the laminates tested. In addition test data and observations will be used in finite element model verification and calibration.

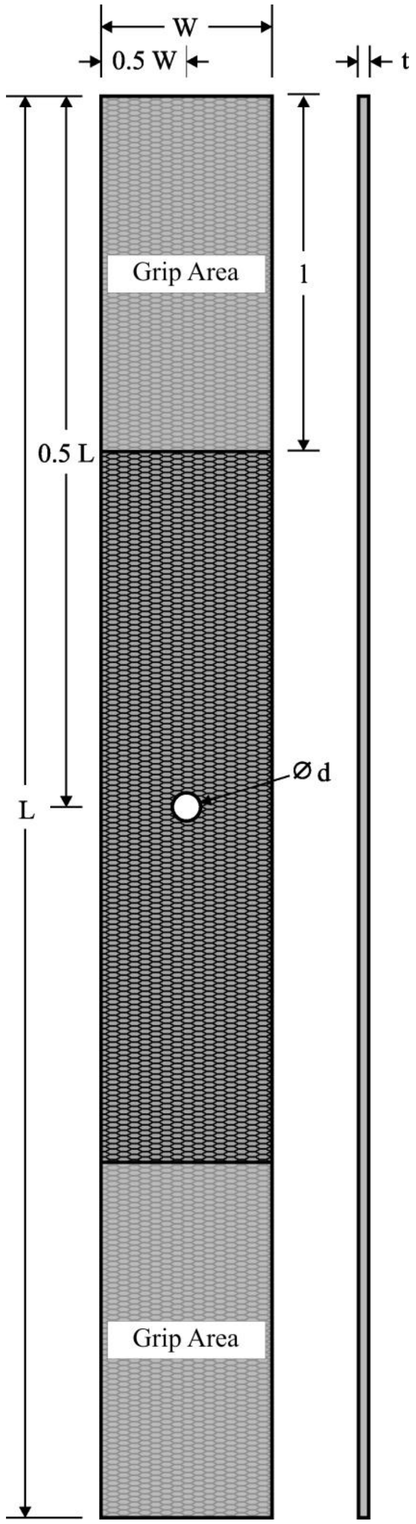
Section 2 presents the experimental methods, including the test plan, specialised jigs, test equipment and data reduction methods. Section 3 presents the results and discussion. Finally Section 4 presents the conclusions from this test series.

Section 2: Experimental Methods

2.1 Test Plan

The specimen geometry is shown in Figure 1. The test procedure and laminate geometry were based on ASTM Standard D5766/D5766M – 02, "Standard Test Method for Open Hole Tensile Strength of Polymer Matrix Composite Laminates" [2]. All specimen dimensions were in accordance with the standard except for those specimens which were being used to study the hole size effects on damage initiation and progression. In these cases the width of the specimens were varied, although a constant specimen width to hole diameter (w/d) ratio of 6 was maintained throughout. Two material systems were examined in this test series. The material examined in Test Series 4a was Hexcel Materials Ltd. 6376C-HTA(12K)-5.5-29.5% carbon fibre reinforced plastic (CFRP). The material examined in Test Series 4b was Cytec Engineered Materials Ltd. FM94-27%-S2-187-460 glass fibre reinforced plastic (GFRP). Note: Test series 1-3 were presented in deliverable D3.2 [1].

Different lay-ups and stacking sequences were investigated for each material system. For the HTA 6376 CFRP the following were considered: one quasi-isotropic (QI) lay-up with stacking sequence $[45/0/-45/90]_{2s}$, two zero-dominated (ZD) lay-ups, ZD_1 and ZD_2, with stacking sequences $[45/0/-45/90/0/0/45/0/-45/0]_s$ and $[45/0/0/-45/90/0/45/0/-45/0]_s$ respectively, and finally, three cross-ply (CP) lay-ups, CP1, CP3 and CP4 with stacking sequences $[90/0]_{4s}$, $[90/0]_{2s}$ and $[90_2/0_2]_s$, respectively. For S2 FM 94 GFRP the following were considered: one quasi-isotropic lay-up with stacking sequence $[45/0/-45/90]_{2s}$, and four cross-ply lay-ups, CP_1, CP_2, CP_3 and CP_4, with stacking sequences $[90/0]_{4s}$, $[90/0]_s$, $[90/0]_{2s}$ and $[90_2/0_2]_s$ respectively. The quasi-isotropic and zero-dominated lay-ups were studied as they are commonly used in the aerospace industry. The cross-ply lay-up was studied, as this is one of the lay-ups used in the fibre metal laminate (FML) GLARE®, of which the S2 FM 94 GFRP is a constituent. Cross-ply lay-up laminates were included in the HTA 6376 CFRP test series so that comparison could be made between material systems. Details on specimen lay-ups and geometry are given in Tables 1 and 2.



Notes: **1.** l – grip length or tab length, this dimension is dependent on the standard to which the coupon is manufactured to.
2. Dimensions for the specimens are given in Tables 1 and 2

Figure 1 Open hole tension specimen geometry

Table 1 Test Matrix for Test Series 4a

			Specimen Geometry									
Code	**Layup**	**Loading**	**L (total)**	**w**	**t**	**d**	**w/d**	**d/t**	**Tabs**	**Instrumentation**	**Percentages of S_{OHT} (%)**	**Number of Tests**
OHT_C_QI_#	QI	Tension	300	36	2.08	6	6	2.9	No	None	95, 85, 75	3
OHT_C_ZD1_#	ZD_1	Tension	300	36	2.6	6	6	2.3	No	None	95, 85, 75	3
OHT_C_ZD1_D3#	ZD_1	Tension	300	18	2.6	3	6	1.2	No	None	95, 85, 75	3
OHT_C_ZD1_D8#	ZD_1	Tension	300	48	2.6	8	6	3.1	No	None	95, 85, 75	3
OHT_C_ZD2_#	ZD_2	Tension	300	36	2.6	6	6	2.3	No	None	95, 85, 75	3
OHT_C_CP1_#	CP_1	Tension	300	36	2.08	6	6	2.9	No	None	95, 80, 65, 55	4
OHT_C_CP3_#	CP_3	Tension	300	36	1.04	6	6	5.8	No	None	95, 85, 75, 65, 55, 40, 25	7
OHT_C_CP4_#	CP_4	Tension	300	36	1.04	6	6	5.8	No	None	95, 85, 75, 65, 55, 40, 25	7
											Total	**33**

- All test specimens are manufactured from HTA/6376 CFRP Prepreg
- All specimen dimensions are given in millimetres
- Layups: QI – $(45/0/-45/90)_{2s}$ ZD_1 - $(45/0/-45/90/0/0/45/0/-45/0)_s$ ZD_2 - $(45/0/0/-45/90/0/45/0/-45/0)_s$
  CP_1 - $(90/0)_{4s}$ CP_3 – $(90/0)_{2s}$ CP_4 – $(90_2/0_2)_s$
- Symbols: # - % of S_{OHT} L – Length w – Width t – Thickness
  d – Hole Diameter *S* – Ultimate Strength
- Subscripts: OHT – Open Hole Tension

Table 2 Test Matrix for Test Series 4b

			Specimen Geometry									
Code	**Layup**	**Loading**	**L (total)**	**w**	**t**	**d**	**w/d**	**d/t**	**Tabs**	**Instrumentation**	**Percentages of S_{OHT} (%)**	**Number of Tests**
OHT_G_QI_#	QI	Tension	300	36	2	6	6	3	No	None	95, 90, 85	3
OHT_G_CP1_#	CP$_1$	Tension	300	36	2	6	6	3	No	None	95, 85, 75	3
OHT_G_CP2_#	CP$_2$	Tension	300	36	0.5	6	6	12	No	None	95, 85, 75, 65, 55, 45, 35, 25	8
OHT_G_CP3_#	CP$_3$	Tension	300	36	1	6	6	6	No	None	95, 85, 75, 65, 55, 45, 35, 25	8
OHT_G_CP4_#	CP$_4$	Tension	300	36	1	6	6	6	No	None	95, 85, 75, 65, 55, 45, 35, 25	8
											Total	**30**

- All test specimens are manufactured from FM94-27%-S2-187-460 GFRP Prepreg
- All specimen dimensions are given in millimetres
- Layups: QI – $(45/0/-45/90)_{2s}$ CP$_1$ - $(90/0)_{4s}$ CP$_2$ – $(90/0)_s$ CP$_3$ – $(90/0)_{2s}$
  CP$_4$ – $(90_2/0_2)_s$
- Symbols: # - Test Number L – Length w – Width t – Thickness
  d – Hole Diameter *S* – Ultimate Strength
- Subscripts: OHT – Open Hole Tension

2.2 Specimen Manufacture and Preparation

All test specimens were manufactured and prepared for testing at the University of Limerick using the Composite Research Centre (CRC) facilities. Panels of the desired lay-up were prepared from rolls of pre-impregnated (prepreg) material, supplied by the manufacturers mentioned above, in a designated, clean environment lay-up room. All panels were then cured according to the manufacturer's instructions in a Leeds and Bradford Boiler Company (LBBC) autoclave. The cured panels were then cut into specimens of the desired dimensions using a designated composite cutting machine with a diamond-coated cutting blade. After cutting, the specimens were cleaned with 600 grit emery cloth and paper towels and measured with digital verniers and micrometers according to the standards [2] to ensure that all specimens were compliant with the dimension tolerances set out in the standards. Holes were then machined in the specimens on a milling machine with the aid of a specially designed drilling jig, using carbide tooling. Holes were first drilled and then reamed to the correct diameter, according to ASTM Standard D5766 [2]. A full description of the method used to machine holes in fibre reinforced polymer matrix composite laminates is presented in Deliverable D3.1a, '*Test Specifications for Material Tests and Open Hole Tests*', [3].

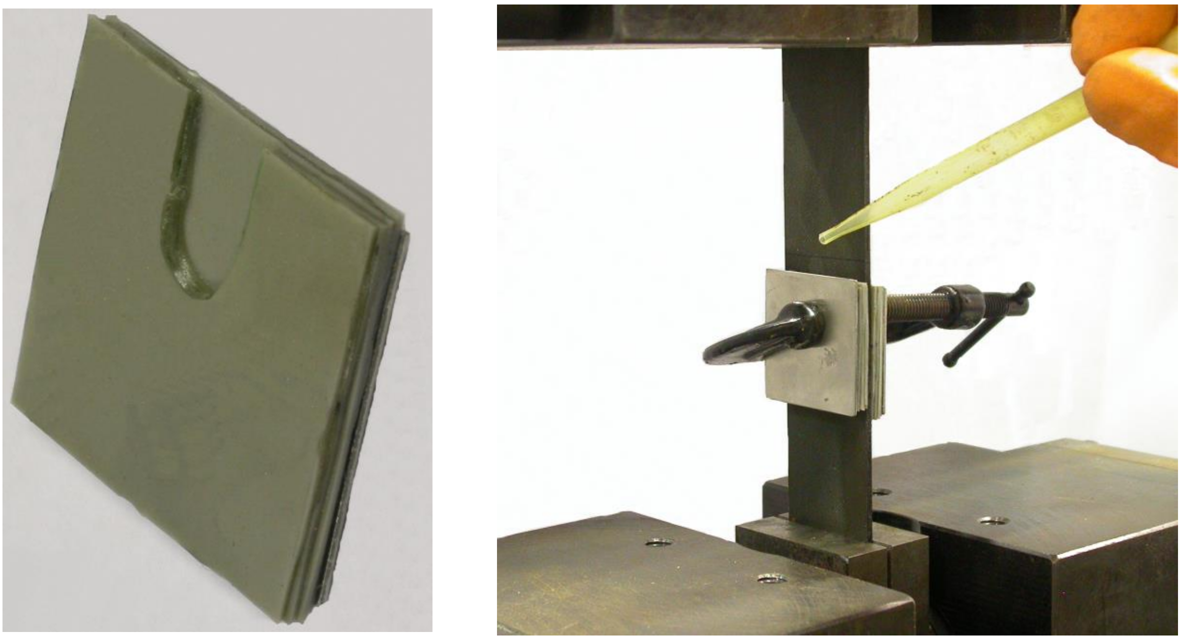
2.3 Test Equipment and Procedure

All open hole tension testing was performed at 0.03mm/s (approximately 2mm/min) on a 100kN Zwick/Roell universal straining frame. Grips on this machine were hydraulically operated and all grips had dedicated composite gripping faces. The grip area dimensions on the straining frame were nominally 75mm by 50 mm. Grip pressures of between 150 – 200 bar were applied to the specimens during loading to prevent slippage within the grips. Figure 2 shows a typical test set-up with a HTA 6376 CFRP open hole tension specimen clamped in the strain frame grips.

Figure 2 Open hole tension specimen clamped in the straining frame grips

Two different non-destructive test methods were used to examine damage in specimens which had been loaded to a percentage of their ultimate strength. The first method used was penetrant radiography, which was used to examine all tested HTA 6376 CFRP open hole tension specimens. The procedure for this method involved loading an open hole tension specimen to a percentage of its ultimate strength. The specimen was then unloaded and two notched rubber blocks, as shown in figure 3*a*, were placed either side of the hole and lightly held in place with a g-clamp so that an open topped reservoir was created in the vicinity of the hole, as shown in figure 3*b*. The specimen was then reloaded to a slightly lower load and Iodomethane 99% penetrant is added to the reservoir created by the rubber blocks. This reloading was carried out so that any damage, such as matrix cracks or delamination, which occurred in the initial loading would reopen. A preliminary study showed that using penetrant on damaged unloaded specimens yielded poor results. Damage such as cracks and delamination did not open sufficiently to allow the iodomentane 99% to penetrate the voids. Care was taken to ensure that more damage was not created upon reloading. Reloading the specimen to approximately 75% of the initial load was sufficient to reopen any damage voids and low enough to ensure that no additional damage occurred. The specimen was kept at this load for approximately ten minutes, which was sufficient time to allow the iodomenthane 99% to penetrate all the damage voids. Care was taken to ensure that the penetrant reservoir was topped up during this time as iodomethane 99% evaporates quickly at room temperature. Once sufficient time had elapsed the specimen was unloaded and removed from the straining frame. The rubber blocks were removed and the specimen was x-rayed in a Hewlett-Packard

Faxitron X-Ray Cabinet using Agfa Structurix D4-FW film. The film was processed using an automatic processor in the usual manner and the developed x-rays were examined in a dark environment using a bright light.



a ***b***

Figure 3; (*a*) Notched rubber block, (*b*) Rubber blocks attached to an open hole tension specimen held in place with a g-clamp. Iodomethane 99% penetrant is added with a disposable dropper.

The second non-destructive method used to examine damaged specimens was visual observation using a bright light source. This method was used exclusively on the S2 FM94 GFRP specimens due to the translucent properties of the S2 FM94 GFRP material, and could not be used on the HTA 6376 CFRP specimens as this material has no translucent property. The procedure for the method was as follows. The specimen which had already been loaded to a percentage of its ultimate strength was removed from the straining frame. Black plasticine was then used to plug the hole in the centre of the laminate and flat black rectangular pieces of plastic with roughly the same dimensions as the laminate were attached to each edge of the laminate using double-sided sticky-tape. The purpose of this was to ensure that when the laminate was placed over a bright light source for examination, most of the light seen comes through the laminate as opposed to around the edges and through the hole. The laminate was then examined using a bright light source usually in a darkened room so as to enhance the light coming through the laminate. Damage in the laminate was observed as shadow. Damage was more easily observed in thin laminates as the light passed through them more easily.

2.4 Data Reduction

Very little data reduction was carried out in this test series as very little measurement equipment was used and most of the results from the test series were qualitative observations rather than quantitative results. However, the following equations were used to determine the loads to which each of the percentage of failure specimens should be loaded to. The cross-sectional area of the specimen, *A*, was determined from thickness, *t*, and width, *w*, measured in the vicinity of the hole. The cross-sectional area was defined according to ASTM standard D5766 [2] as the gross cross-sectional area of the laminate, including the cross-sectional area of the hole.

$$A = w \times t \qquad \text{(Eqn. 2.1)}$$

The load, *P*, to which the open hole tension specimens were to be loaded to was determined from the following equation:

$$P = A\sigma_{\%} \qquad \text{(Eqn. 2.2)}$$

where A is the specimen cross-sectional area and $\sigma_{\%}$ is the percentage of the specimen ultimate strength it was to be loaded to.

Section 3: Results and Discussion

For ease of presentation of results this section is divided into a number of parts. Firstly, in Part 3.1, the results from penetrant radiography of the HTA 6376 CFRP open hole tension specimens are presented and discussed. In Part 3.2 the results of the backlight examination of the S2 FM94 GFRP open hole tension specimens are presented and discussed, and finally in Part 3.3 the common trends noticed in both material systems are discussed in addition to the influence that the damage progression observed in the different laminates has on their overall open hole tensile strength.

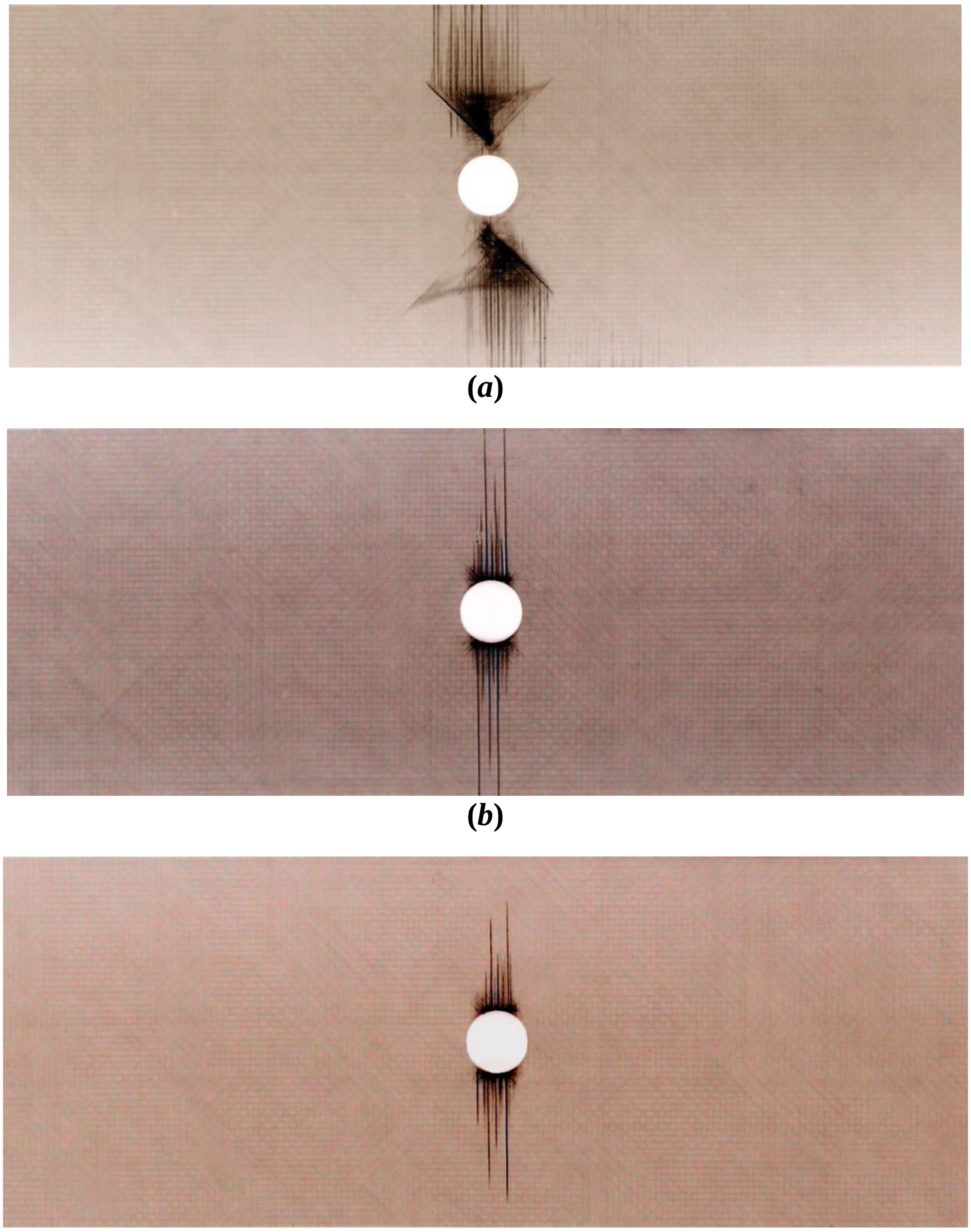
3.1 Penetrant Radiography Results for HTA 6376 CFRP Open Hole Tension Specimens

For ease of presentation this part is divided into a number of sub-parts, in each of which, penetrant radiography results are presented for a different lay-up. Observations about the type and extent of damage for each lay-up are discussed within the relevant subpart.

3.1.1 Damage Progression in HTA 6376 CFRP Quasi-Isotropic Open Hole Tension Specimens

Three HTA 6376 CFRP open hole tension quasi-isotropic specimens were tested to different percentages of failure strength: 95%, 85% and 75%, respectively, to determine damage progression for this type of lay-up. The penetrant radiography results for each of these tests are presented in figures 4*a*, 4*b* and 4*c* respectively.

It can clearly be seen that damage in this laminate lay-up is characterised by matrix cracks in the 90° and ±45° plies, while matrix splitting does not appear to be evident in the 0° plies. In addition significant delamination is evident in the laminate just prior to failure. Looking at the progression of damage from 75% of S_{OHT} to 95% of S_{OHT} it is evident that most of the damage in the 75% and 85% radiographs, other than some long matrix cracks in the 90° plies, is confined to the region in the vicinity of the hole. This suggests that the stress concentration is still largest at either side of the hole. In addition there appears to be no great change in size of the damage zone between 75% and 85% of S_{OHT}. However, there is significant growth in the damage zone between 85% and 95% of S_{OHT}; the matrix cracks in the ±45° plies have extended significantly and are accompanied by a large triangular region of delamination on each side of the hole. This increase in the damage zone appears to occur very rapidly and at loads just below the ultimate failure load of the laminate. This suggests that the onset of failure for an open-hole laminate of this lay-up is accompanied by rapid and catastrophic damage growth.



(*a*)

(*b*)

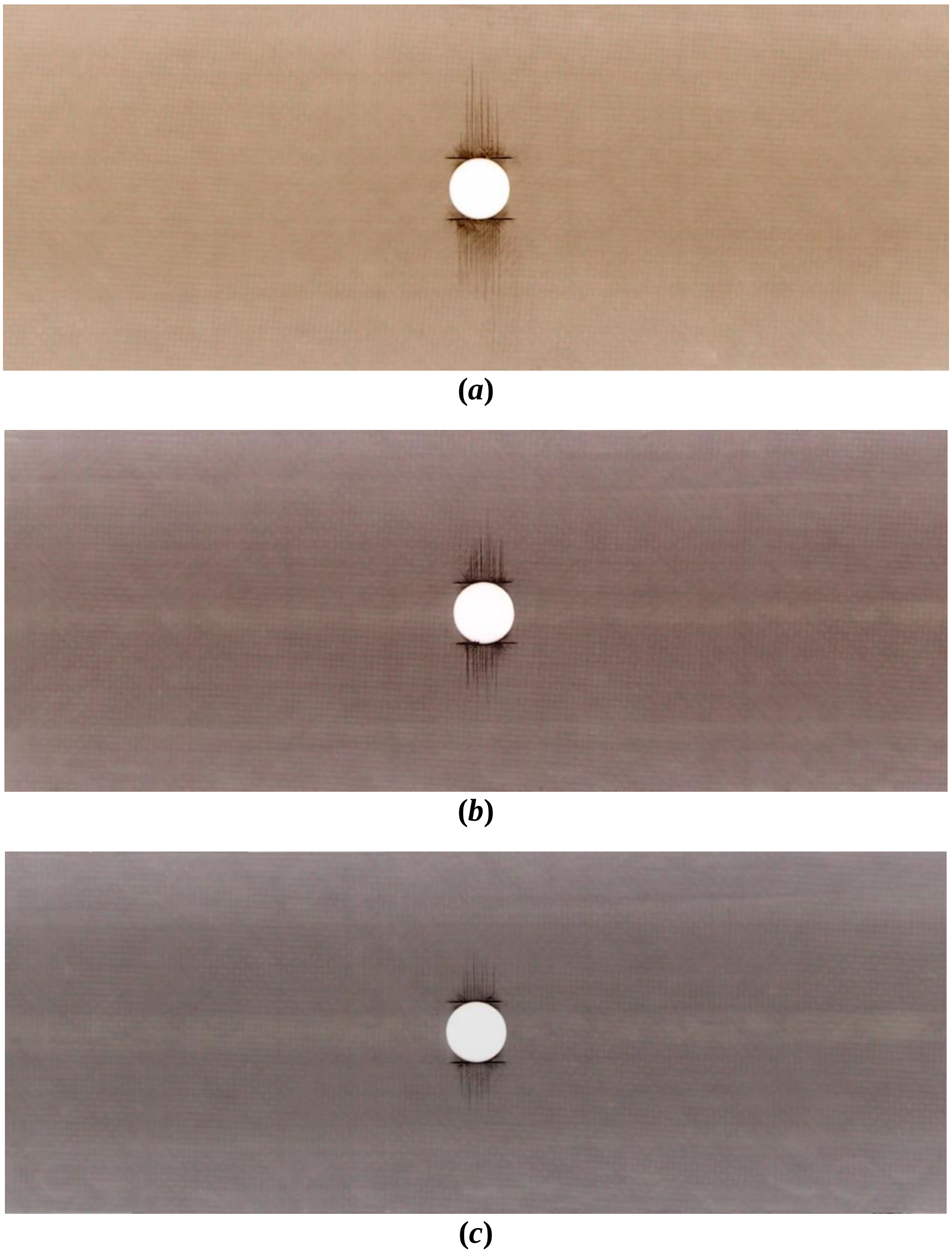
(*c*)

Figure 4; HTA 6376 CFRP quasi-isotropic open hole tension specimen tested to (*a*) 95% of S_{OHT}, (*b*) 85% of S_{OHT}, and (*c*) 75% of S_{OHT}.

3.1.2 Damage Progression in HTA 6376 CFRP Zero Dominated ZD_1 Open Hole Tension Specimens

As with the quasi-isotropic specimens, three HTA 6376 CFRP zero dominated ZD_1 open hole tension specimens were tested to three different percentages of failure, 95%, 85% and 75%, respectively, to determine damage progression for this type of lay-up. The penetrant radiography results for each of these tests are presented in figures 5*a*, 5*b* and 5*c* respectively.

It can clearly be seen that damage in this laminate lay-up is characterised by matrix cracks in the 0° plies on either side of the hole, in addition to some minor matrix cracks in the 90° and ±45° plies. No significant amount of delamination is evident in any of the radiographs. Looking at the progression of damage from 75% of S_{OHT} to 95% of S_{OHT} it is evident that the damage zone growth is stable and almost insignificant. The matrix cracks in the 0° plies do not appear to grow significantly over the range of loads, and the only damage growth appears to be in the increased length of the matrix cracks in the 90° plies. This is in contrast with the damage growth observed in the quasi-isotropic specimens, which have quite a similar lay-up to this laminate, where damage growth was rapid and unstable prior to ultimate failure. The difference in damage progression must be attributed to the additional 0° plies contained in the ZD_1 lay-up. Matrix cracking in these additional 0° plies appears to have blunted the stress concentration in the laminate due to the hole, therefore, inhibiting damage growth in the form of matrix cracking in the off-axis plies and delamination.



(*a*)

(*b*)

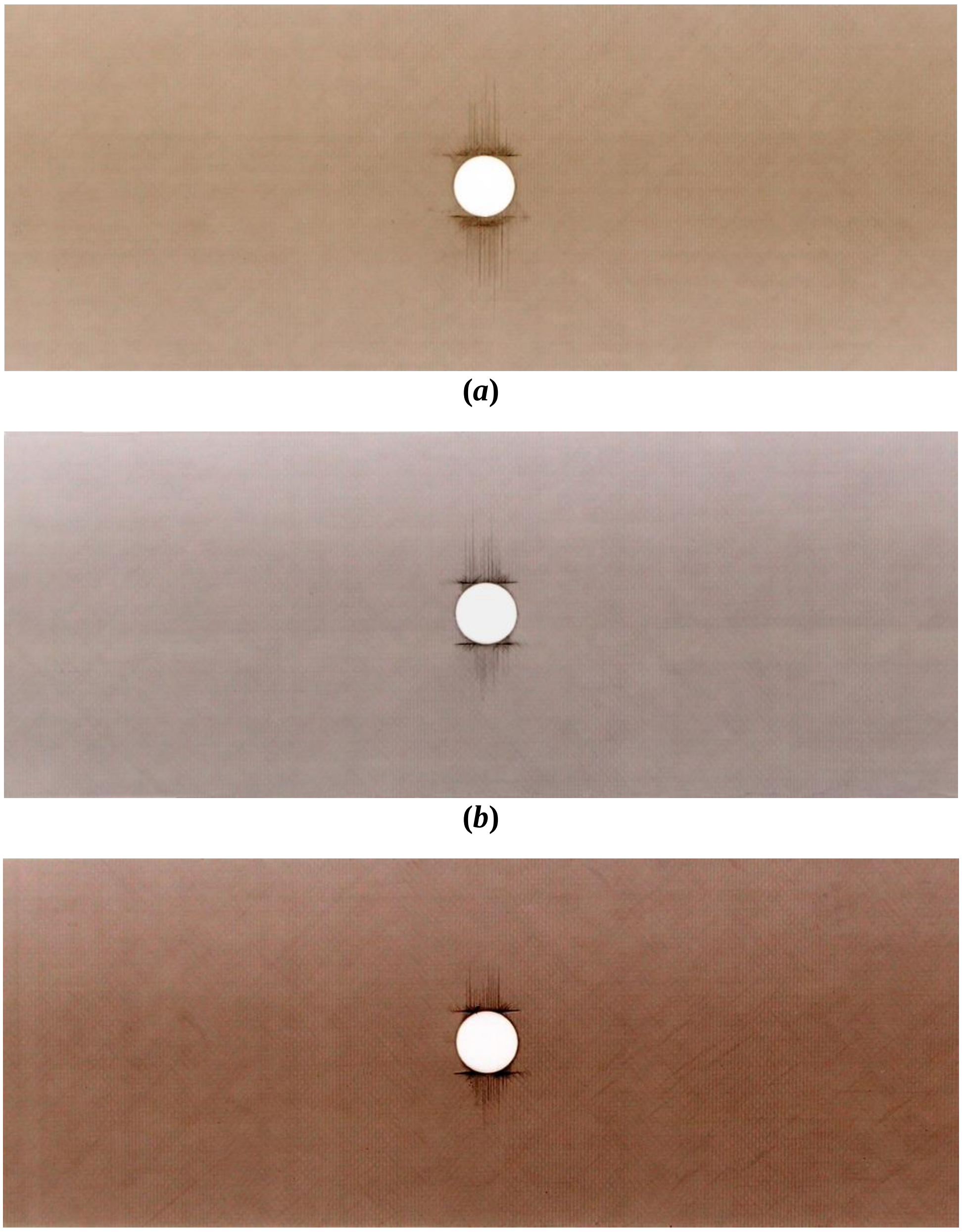
(*c*)

Figure 5; HTA 6376 CFRP ZD$_1$ open hole tension specimen tested to (*a*) 95% of S_{OHT}, (*b*) 85% of S_{OHT}, and (*c*) 75% of S_{OHT}.

3.1.3 Damage Progression in HTA 6376 CFRP Zero Dominated ZD_2 Open Hole Tension Specimens

HTA 6376 CFRP zero dominated ZD_2 open hole tension specimens were tested to three different percentages of failure, 95%, 85% and 75%, respectively, to determine damage progression for this type of lay-up. The penetrant radiography results for each of these tests are presented in figures 6*a*, 6*b* and 6*c* respectively.

The zero dominated ZD_2 laminate has the same lay-up as the ZD_1 laminate, but the stacking sequence differs by the fact that the ZD_2 laminate has its additional 0° plies near the surface of the laminate, whereas the ZD_1 laminate has its additional plies near the centre of the laminate. From examination of the radiographs it appears that there is no significant difference between the damage progression observed for the ZD_1 laminate and the damage observed for the ZD_2 laminate.



(*a*)

(*b*)

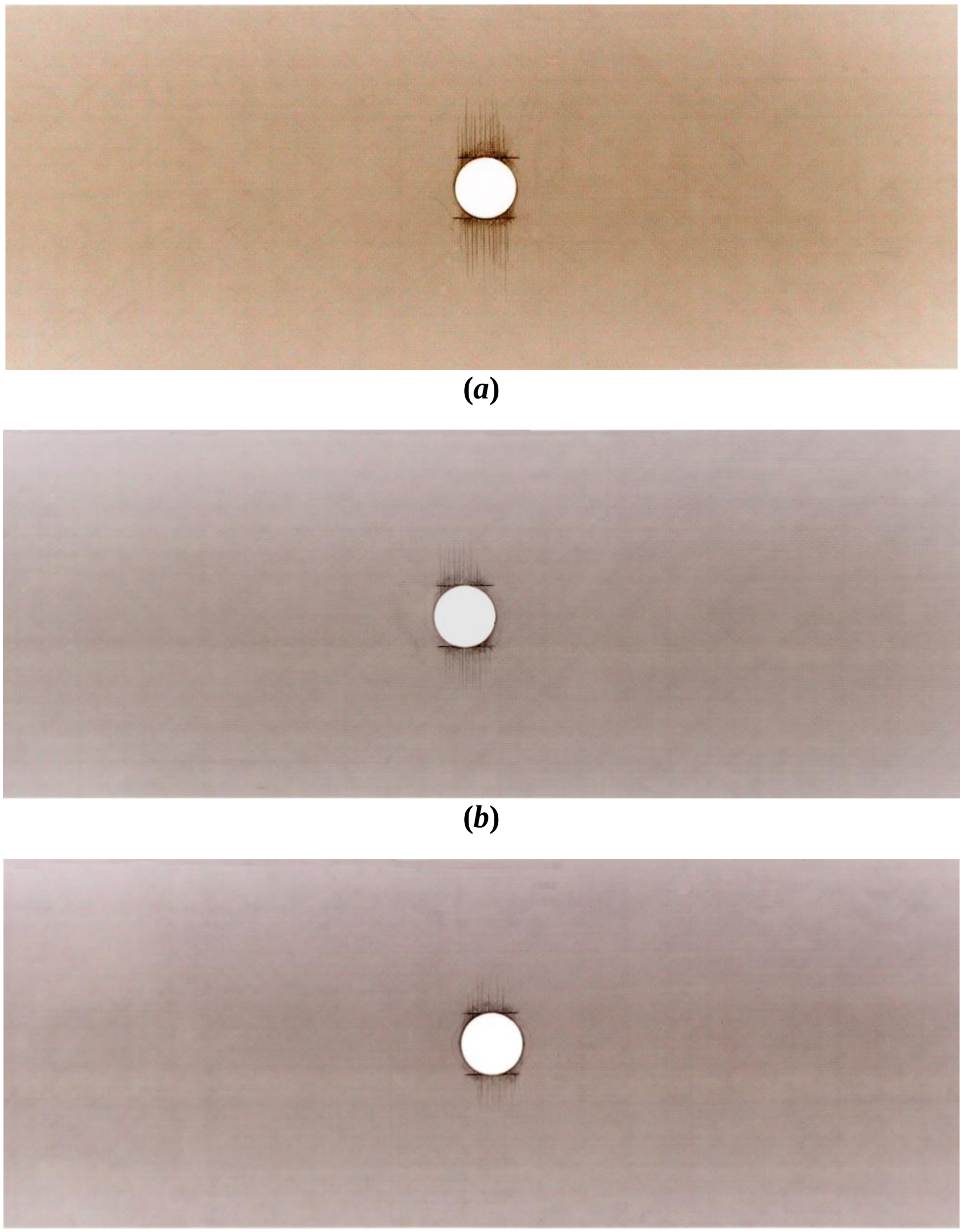
(*c*)

Figure 6; HTA 6376 CFRP ZD$_2$ open hole tension specimen tested to (*a*) 95% of S_{OHT}, (*b*) 85% of S_{OHT}, and (*c*) 75% of S_{OHT}.

3.1.4 Damage Progression in HTA 6376 CFRP Zero Dominated ZD_1 D8mm Open Hole Tension Specimens

HTA 6376 CFRP zero dominated ZD_1 D8 mm open hole tension specimens were tested to three different percentages of failure, 95%, 85% and 75%, respectively, to determine damage progression for this type of lay-up. The penetrant radiography results for each of these tests are presented in figures 7*a*, 7*b* and 7*c* respectively.

This laminate has the same lay-up as the ZD_1 laminate discussed in 3.1.2 above but the width and hole diameter of this laminate are 1.33 times larger. The damage characteristics are similar to that of the ZD_1 specimen, i.e. matrix cracks in the 0° plies either side of the hole accompanied by minor matrix cracks in the 90° and ±45° plies. However, it should be noted that the length of the matrix cracks in the 0° plies are slightly shorter, relative to the hole diameter, than those observed in the ZD_1 specimen.



(*a*)

(*b*)

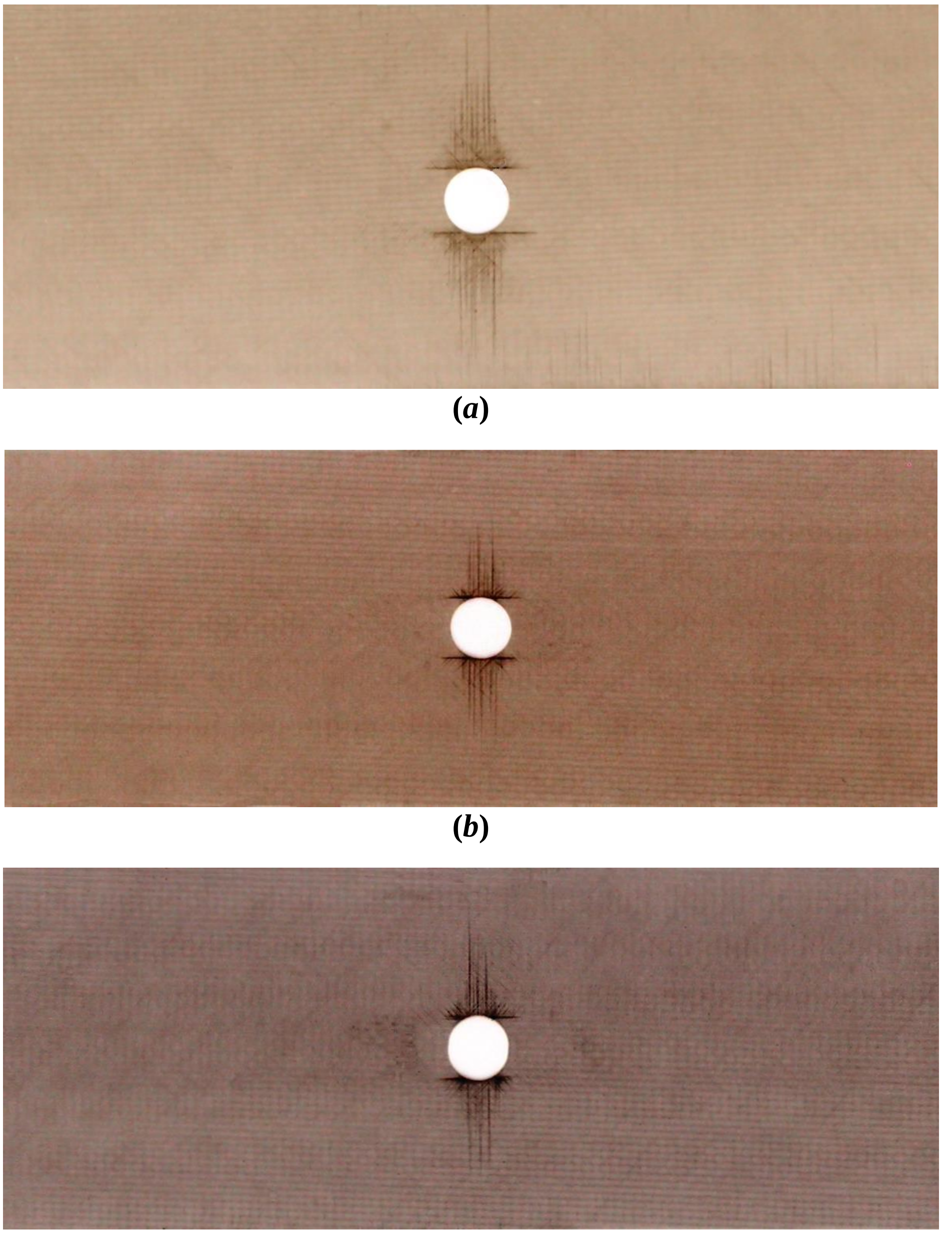
(*c*)

Figure 7; HTA 6376 CFRP ZD$_1$ D8 mm open hole tension specimen tested to (*a*) 95% of S_{OHT}, (*b*) 85% of S_{OHT}, and (*c*) 75% of S_{OHT}.

3.1.5 Damage Progression in HTA 6376 CFRP Zero Dominated ZD_1 D3mm Open Hole Tension Specimens

HTA 6376 CFRP zero dominated ZD_1 D3 mm open hole tension specimens were tested to three different percentages of failure, 95%, 85% and 75%, respectively, to determine damage progression for this type of lay-up. The penetrant radiography results for each of these tests are presented in figures 8*a*, 8*b* and 8*c* respectively.

Again, this laminate is essentially the same as the ZD_1 laminate discussed in 3.1.1 above except that the width and hole diameter of this laminate are half that of the ZD_1 laminate. The damage characteristics are similar to that of the ZD_1 laminate, i.e. matrix cracks in the 0° plies either side of the hole accompanied by minor matrix cracks in the 90° and ±45° plies. However, it should be noted that the length of the matrix cracks in the 0° plies are slightly longer, relative to the hole diameter, than those observed in the ZD_1 specimen and the damage zone in general appears slightly larger, relative to the hole diameter.



(*a*)

(*b*)

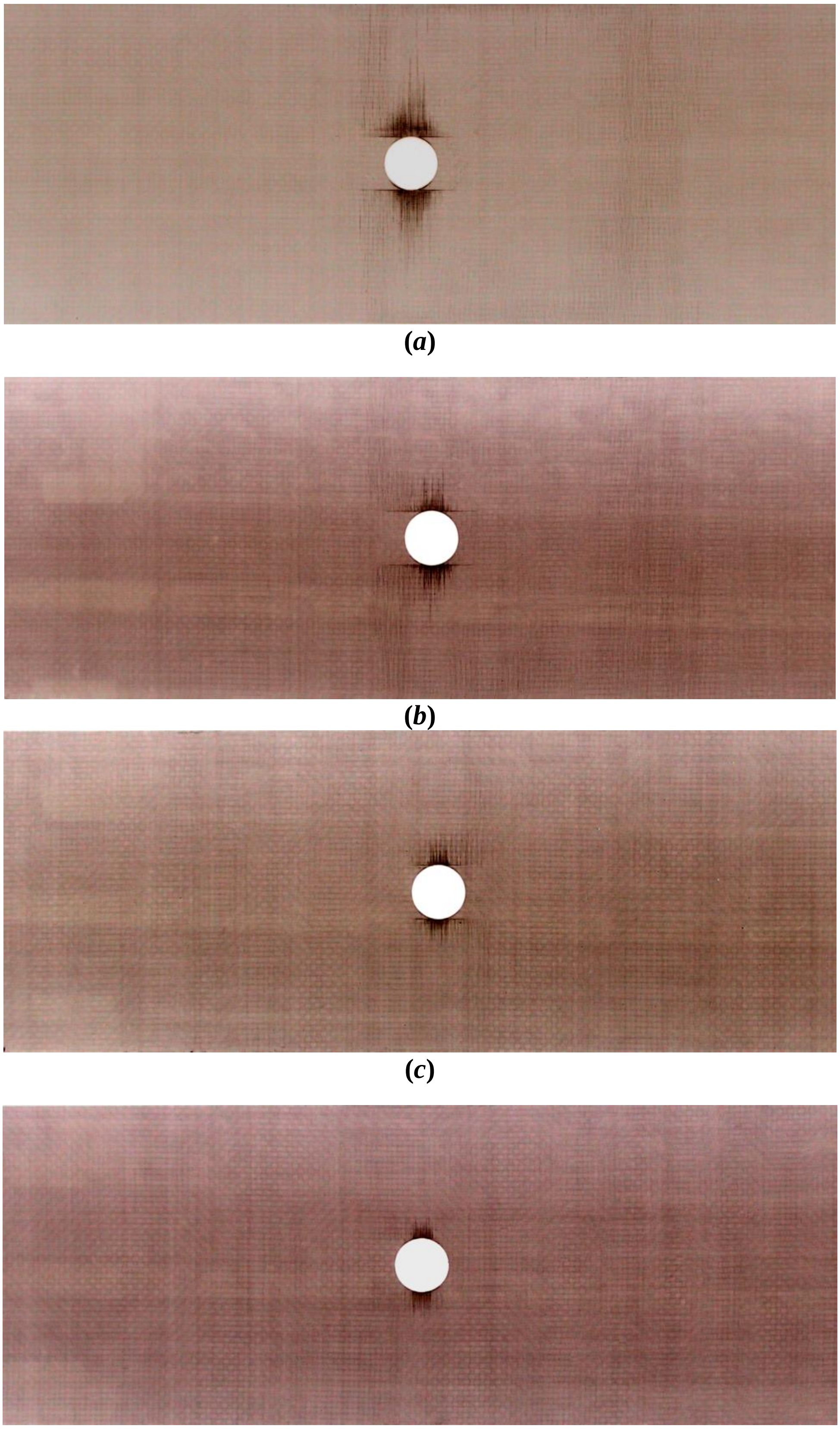
(*c*)

Figure 8; HTA 6376 CFRP ZD$_1$ D3 mm open hole tension specimen tested to (*a*) 95% of S_{OHT}, (*b*) 85% of S_{OHT}, and (*c*) 75% of S_{OHT}.

3.1.6 Damage Progression in HTA 6376 CFRP Cross-Ply CP_1 Open Hole Tension Specimens

HTA 6376 CFRP cross-ply CP_1 open hole tension specimens were tested to four different percentages of failure, 95%, 80%, 65% and 55%, respectively, to determine damage progression for this type of lay-up. The penetrant radiography results for each of these tests are presented in figures 9*a*, 9*b*, 9*c* and 9*d* respectively.

Unlike the laminates examined above this laminate has no ±45° plies. It is evident from the radiographs that the damage in this laminate lay-up is characterised by matrix cracks in both the 0° and 90° plies on either side of the hole. Looking at the progression of damage through the radiographs taken at different percentages of failure, it can be seen that damage is initiated in the form of matrix cracks in the 90° plies on either side of the hole. Between 55% and 65% of the ultimate failure strength of the laminate, matrix cracks occur in the 0° plies on either side of the hole. There appears to be no increase in the number or size of matrix cracks in the 90° plies at this load level suggesting that the matrix cracks in the 0° plies have blunted the stress concentration due to the hole. At approximately 80% of the ultimate strength of the laminate the matrix cracks in the 0° plies have extended significantly. In addition there is a slight increase in the amount of matrix cracks in the 90° plies, which appear to be accompanied by some localised delamination in the vicinity of the hole. At approximately 95% of the ultimate load the matrix cracks in the 0° plies adjacent to the hole appear to be roughly the same length as they were at approximately 80% of the ultimate failure strength. However, there is evidence of the initiation of new matrix cracks in the 0° plies away from the immediate vicinity of the hole. In addition, the number of matrix cracks in the 90° plies, has increased in number and length. In general the damage zone adjacent to the hole has increased perpendicularly to the direction of loading of the laminate.



(*a*)

(*b*)

(*c*)

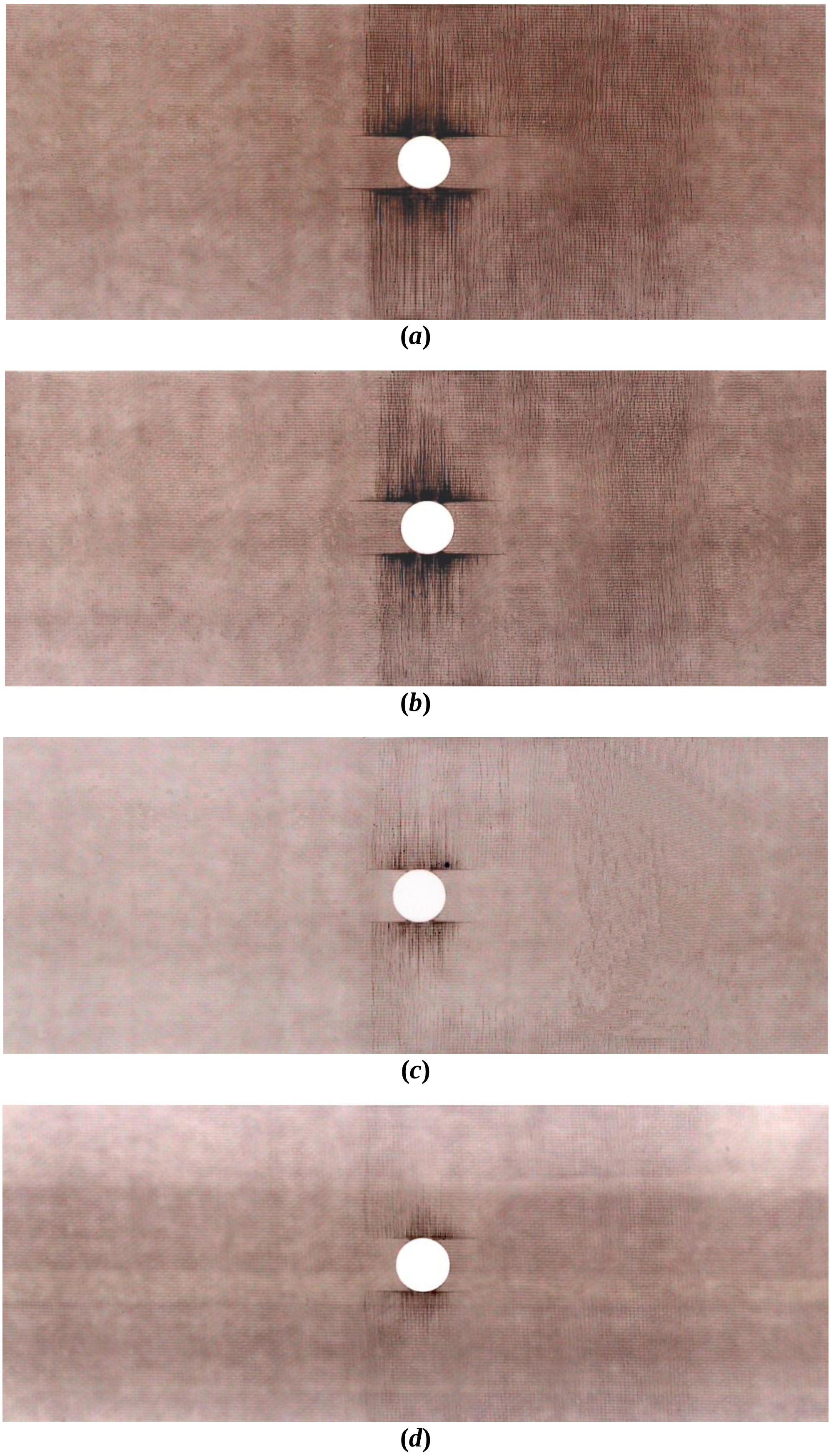
(*d*)

Figure 9; HTA 6376 CFRP CP$_1$ open hole tension specimen tested to (*a*) 95% of S_{OHT}, (*b*) 80% of S_{OHT}, (*c*) 65% of S_{OHT} and (*d*) 55% of S_{OHT}.

3.1.7 Damage Progression in HTA 6376 CFRP Cross-Ply CP_3 Open Hole Tension Specimens

HTA 6376 CFRP cross-ply CP_3 open hole tension specimens were tested to seven different percentages of failure, 95%, 85%, 75%, 65%, 55%, 40% and 25%, respectively, to determine damage progression for this type of lay-up. The penetrant radiography results for each of these tests are presented in figures 10*a*, 10*b*, 10*c*, 10*d*, 10*e*, 10*f* and 10*g* respectively.

This laminate is similar in stacking sequence to CP_1 laminate, but it has less half as many plies and is therefore significantly thinner. As such, it displays similar damage characteristics as the CP_1 laminate, i.e. damage is characterised by matrix cracks in both the 0° and 90° plies. Looking at the individual radiographs for different percentages of ultimate strength; in the 25% and 40% radiographs dark regions at the both sides of the holes suggest initiation of damage in the form of matrix cracks in the 90° plies. Between 40% and 55% of the ultimate strength of the laminate matrix cracks have initiated and grown in the 0° plies adjacent to the hole. These appear to have blunted the stress concentration due to the hole, as there does not appear to be any significant increase in the volume of matrix cracks in the 90° plies. The matrix cracks in the 0° plies adjacent to the hole increase in length steadily through 65% and 75% of the ultimate strength of the laminate. They are accompanied by the initiation of matrix cracks in the 90° plies along their length. At approximately 85% of the ultimate strength, the matrix cracks in the 0° plies adjacent to the hole have increase in length and are accompanied by a significant increase in the number and length of matrix cracks in the 90° plies. In addition, triangular regions of delamination can be seen extending from the tip of the cracks in the 0° plies to the edge of the hole. At approximately 95% of the ultimate strength, there appears to be no significant increase in the length of the cracks in the 0° plies, however, the volume and length of the matrix cracks in the 90° plies has increased and is accompanied by an apparent increase in the triangular regions of delamination adjacent to the hole. Note also in the 85% and 95% of ultimate strength radiographs the region of what appears to be matrix cracking in the 90° plies to the right of the hole. This area was wetted with penetrant by capillary action when the hole was being soaked in penetrant. It is the author’s opinion that penetrant has soaked into surface matrix cracks in the 90° plies, which now appear in the radiograph. In addition, note that there appears to be no damage in the region adjacent to the hole fenced by the matrix cracks in the 0° plies. This lack of damage suggests that this region is subjected to relatively low stresses due to the blunting of the stress concentration around the hole by the matrix cracks in the 0° plies.



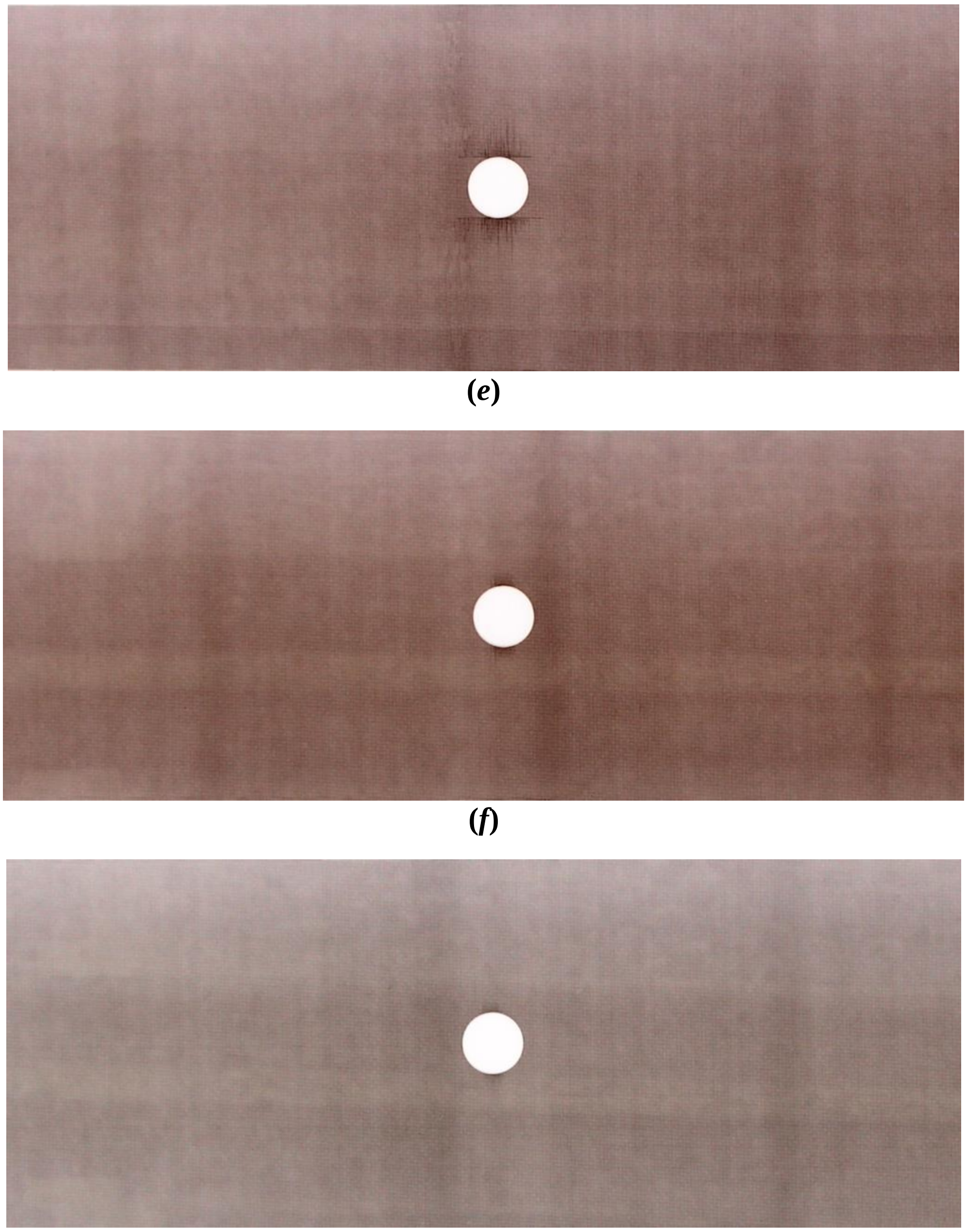
(*a*)

(*b*)

(*c*)

(*d*)

Figure 10, see next page for caption


(*e*)

(*f*)

(*g*)

Figure 10; HTA 6376 CFRP CP3 open hole tension specimen tested to (*a*) 95% of S_{OHT}, (*b*) 85% of S_{OHT}, (*c*) 75% of S_{OHT} (*d*) 65% of S_{OHT}, (*e*) 55% of S_{OHT}, (*f*) 40% of S_{OHT} and (*g*) 25% of S_{OHT}.

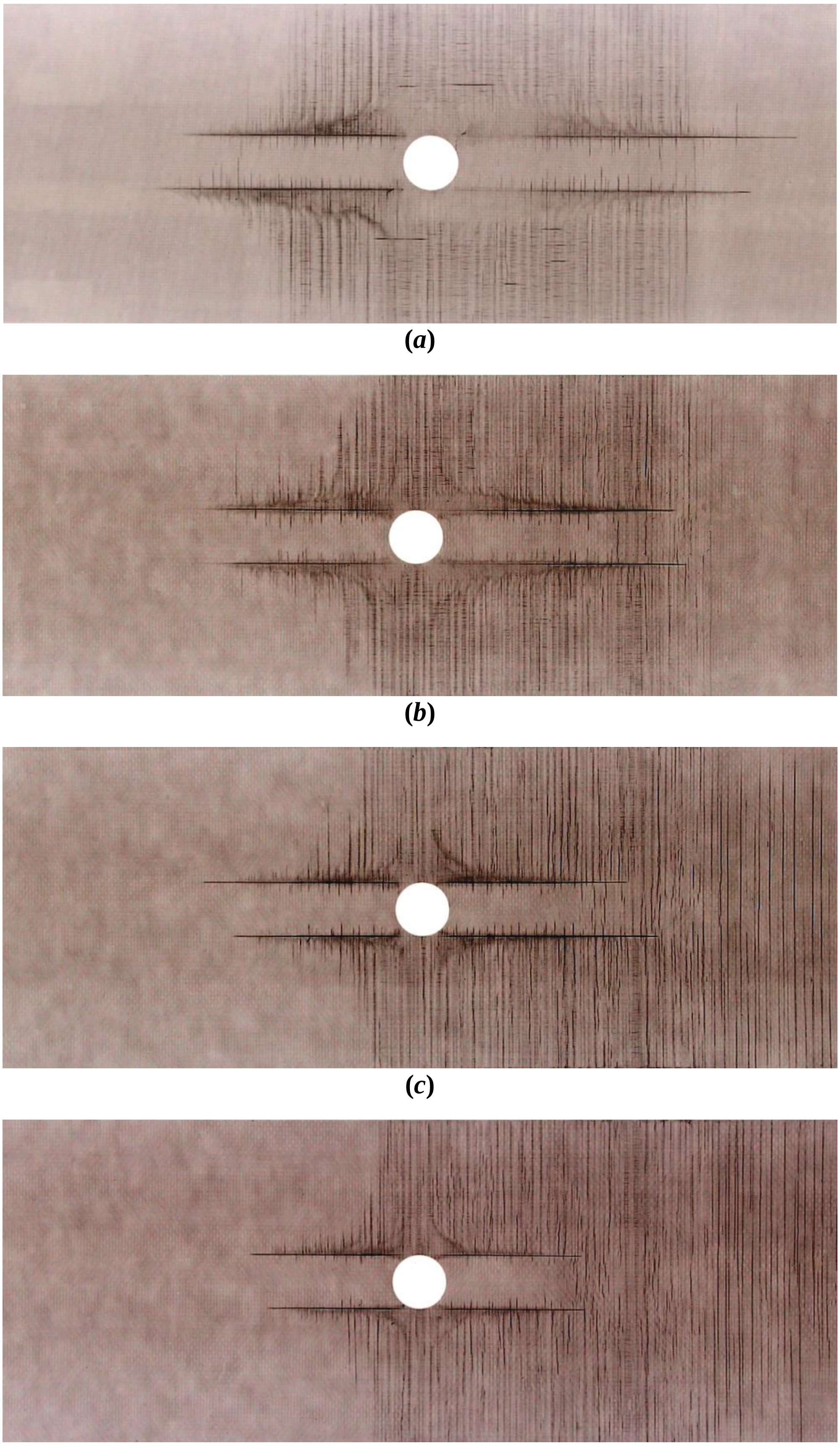
3.1.8 Damage Progression in HTA 6376 CFRP Cross-Ply CP_4 Open Hole Tension Specimens

HTA 6376 CFRP cross-ply CP_3 open hole tension specimens were tested to seven different percentages of failure, 90%, 85%, 75%, 65%, 55%, 40% and 25%, respectively, to determine damage progression for this type of lay-up. The penetrant radiography results for each of these tests are presented in figures 11*a*, 11*b*, 11*c*, 11*d*, 11*e*, 11*f* and 11*g* respectively.

This laminate is similar to the CP_3 laminate in so far as both laminates each contain the same number of 0° plies and the same number of 90° plies. They differ however, in the sequence in which these plies are stacked. The CP_3 laminate has an alternating stacking sequence, i.e. 90°, 0°, 90°, 0°, whereas the CP4 laminate has a blocked stacking sequence, i.e. 90°, 90°, 0°, 0°. From examination of radiographs of both laminates it is evident that this does not affect the nature of the damage evident in either laminate, as damage in both laminates is characterised by matrix cracks in the 0° and 90° plies. However, it does affect the extent and volume of damage observed in both. It is clear that the CP_4 laminate is susceptible to much longer matrix cracks in the 0° plies and a greater volume of longer matrix cracks in the 90° plies than the CP_3 laminate.

Looking at the individual radiographs of the CP_4 laminate taken at different percentages of ultimate strength, it can be seen that there is very little hint of damage initiation at 25% of the ultimate strength. However, examination of the radiograph taken at approximately 40% of the ultimate strength shows matrix cracks in the 0° plies adjacent to the hole almost as long as those observed in the radiograph of the CP_3 laminate at 95% of ultimate strength. In addition, this is accompanied by matrix cracks in the 90° plies, which extend from the hole almost to the edge of the laminate. The matrix cracks adjacent to the hole in the 0° plies continue to extend through 55% and 65% of the ultimate load and begin to appear darker on the radiographs suggesting that they are becoming wider and gaining depth through the laminate. Growth of the matrix cracks adjacent to the hole in the 0° plies, is accompanied by an increase in the volume and length of matrix cracks in the 90° plies. Note the appearance on the right side of the radiograph, taken at 65% of the ultimate strength, of matrix cracks in the 90° plies away from the vicinity of the hole. It is believed that these are matrix cracks in the surface 90° plies. Note how these cracks appear more plentiful and wider than those observed in the CP_3

laminate. The length of the matrix cracks adjacent to the hole in the 0° plies continues to increase through 75%, 85% and 90% of the ultimate strength. Note also at these loads the appearance of a triangular ‘tide mark’ adjacent to the matrix cracks in the 0° plies, which is particularly evident in the 85% of the ultimate load radiograph, figure 11*b*. It is the author’s opinion that this is the outline of a triangular region of delamination extending from the tips of the matrix cracks in the 0° plies to the edge of the hole. It is believed that this region of delamination is not better highlighted in the radiograph because most of the penetrant may have been squeezed out of the delamination void as the specimen was unloaded so that it could be placed in the x-ray cabinet and most of the remainder evaporated. This is also felt to be the reason why parts of the matrix cracks in the 90% of ultimate strength radiograph are not fully highlighted. Again, note that there appears to be no damage in the region adjacent to the hole fenced by the matrix cracks in the 0° plies, suggesting the blunting of the stress concentration around the hole by the matrix cracks in the 0° plies.



(*a*)

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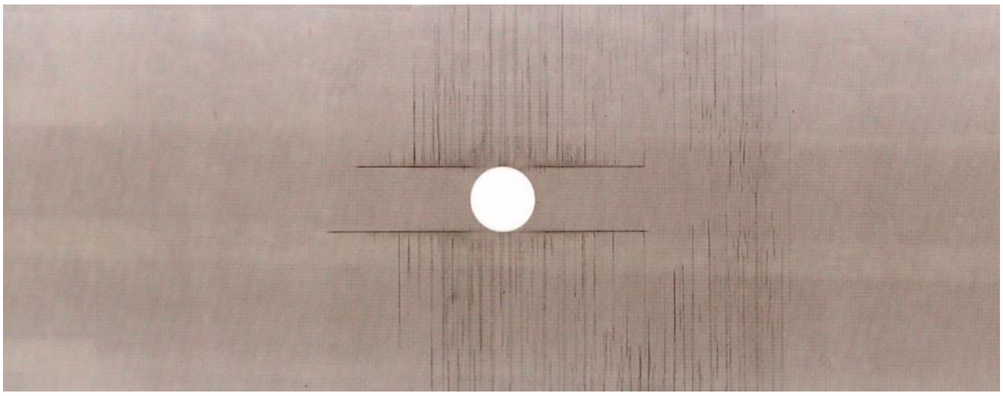
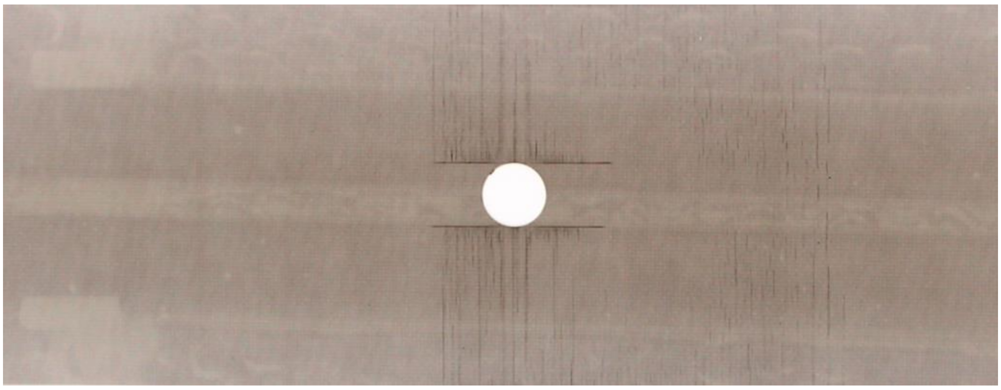
Figure 11, see next page for caption



(*e*)



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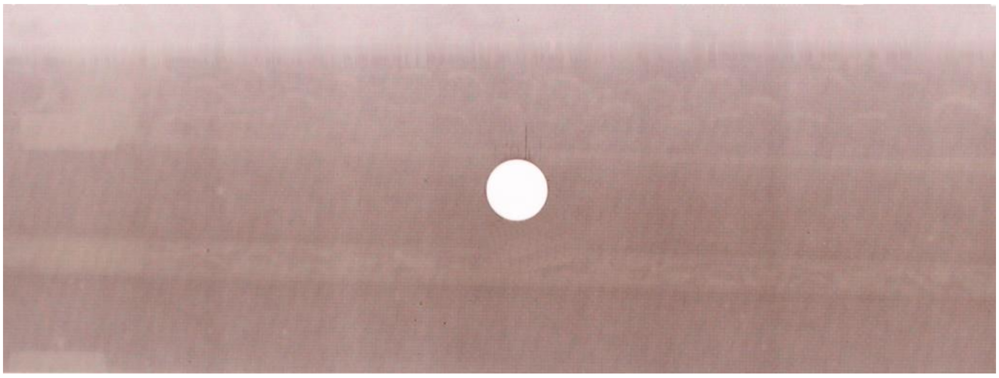


(*g*)

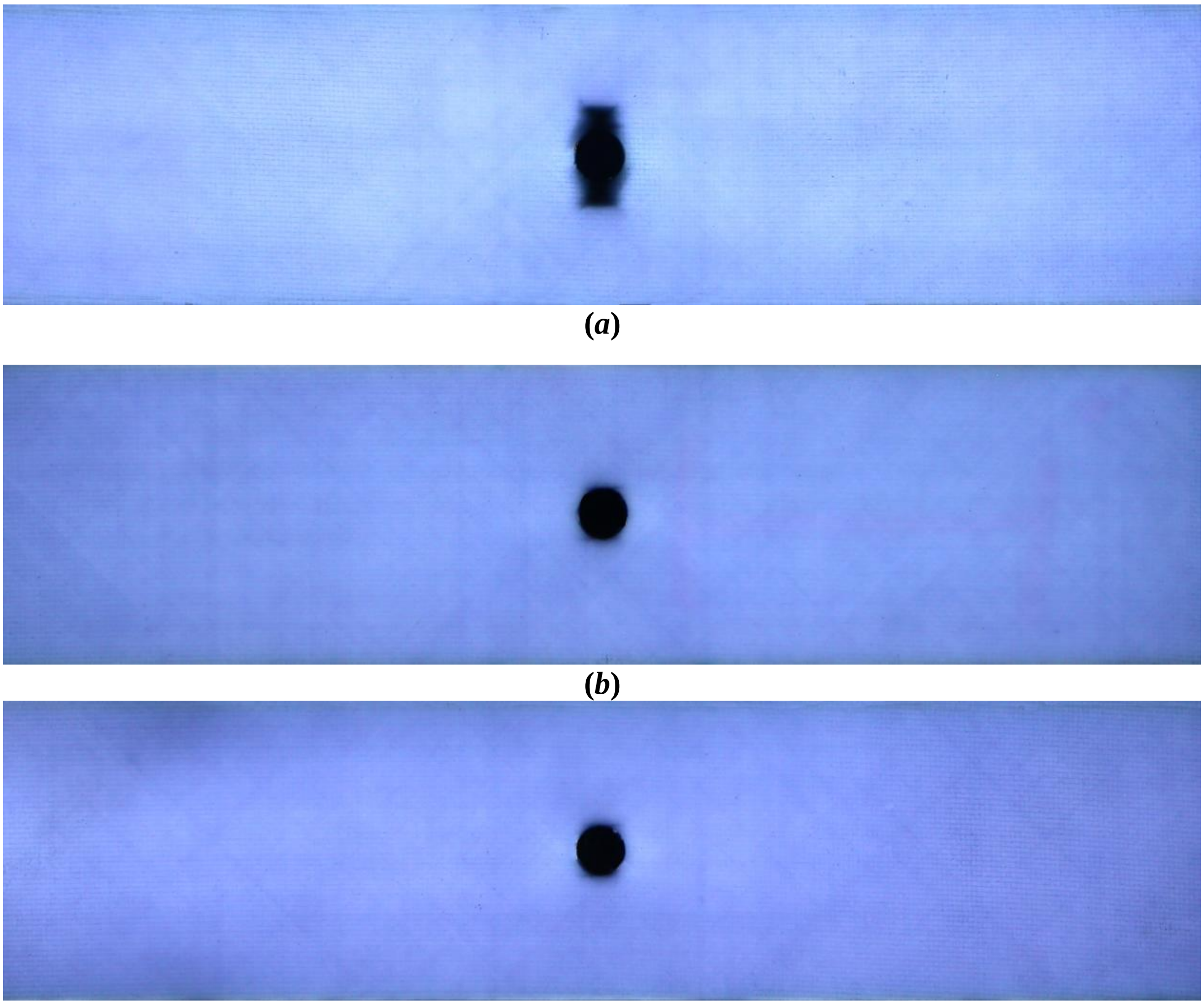
Figure 11; HTA 6376 CFRP CP4 open hole tension specimen tested to (*a*) 95% of S_{OHT}, (*b*) 85% of S_{OHT}, (*c*) 75% of S_{OHT} (*d*) 65% of S_{OHT}, (*e*) 55% of S_{OHT}, (*f*) 40% of S_{OHT} and (*g*) 25% of S_{OHT}.

3.2 Backlight Observation Results for S2 FM94 GFRP Open Hole Tension Specimens

For ease of presentation this part is divided into a number of sub-parts, in each of which, backlight observation results are presented for a different lay-up. Observations about the type and extent of damage for each lay-up are discussed within the relevant sub-part.

3.2.1 Damage Progression in S2 FM94 GFRP Quasi-Isotropic Open Hole Tension Specimens

S2 FM94 GFRP quasi-isotropic open hole tension specimens were tested to three different percentages of failure, 95%, 90%, and 85%, respectively, to determine damage progression for this type of lay-up. The backlight observation results for each of these tests are presented in figures 12*a*, 12*b* and 12*c*, respectively.



(*a*)

(*b*)

(*c*)

Figure 12; S2 FM94 GFRP quasi isotropic open hole tension specimen tested to (*a*) 95% of S_{OHT}, (*b*) 90% of S_{OHT} and (*c*) 85% of S_{OHT}.

Characteristic damage for this laminate appears to be delamination accompanied by matrix cracks in the 90°and ±45° plies. Examination of backlight images taken at 85% and 90% of the ultimate failure strength shows that very little damage occurs in the laminate at these load levels other than some minor matrix cracking in the 90°and ±45° plies in the region adjacent to the hole. However, a backlight image taken at 95% of the ultimate strength shows a significant increase in damage. The damage appears as two square regions of matrix cracking and delamination on either side of the hole and appears to be progressing in a direction perpendicular to the direction of loading. Examination of the backlight images suggests that there is no blunting of the stress concentration at the hole by damage during loading and that failure of the laminate is characterised by a rapid unstable growth of damage within the laminate prior to ultimate failure.

3.2.2 Damage Progression in S2 FM94 GFRP Cross-Ply CP_1 Open Hole Tension Specimens

S2 FM94 GFRP cross-ply CP_1 open hole tension specimens were tested to three different percentages of failure, 95%, 85%, and 75%, respectively, to determine damage progression for this type of lay-up. The backlight observation results for each of these tests are presented in figures 13*a*, 13*b* and 13*c*, respectively.

Damage in this laminate is characterised by long matrix cracks in the 0° plies adjacent to the hole. This damage shows up in the backlight images in figure 13 as long shadows emanating from the edges of the hole in the direction of loading. The length and definition of the shadow is seen to increase with increasing percentage of ultimate strength. No other forms of damage are immediately evident in the backlight images other than what appears to be some minor matrix cracks in the 90° plies and some minor delamination in the vicinity of the hole, suggesting that the stress concentration due to the hole has been blunted by the matrix cracks in the 0° plies.

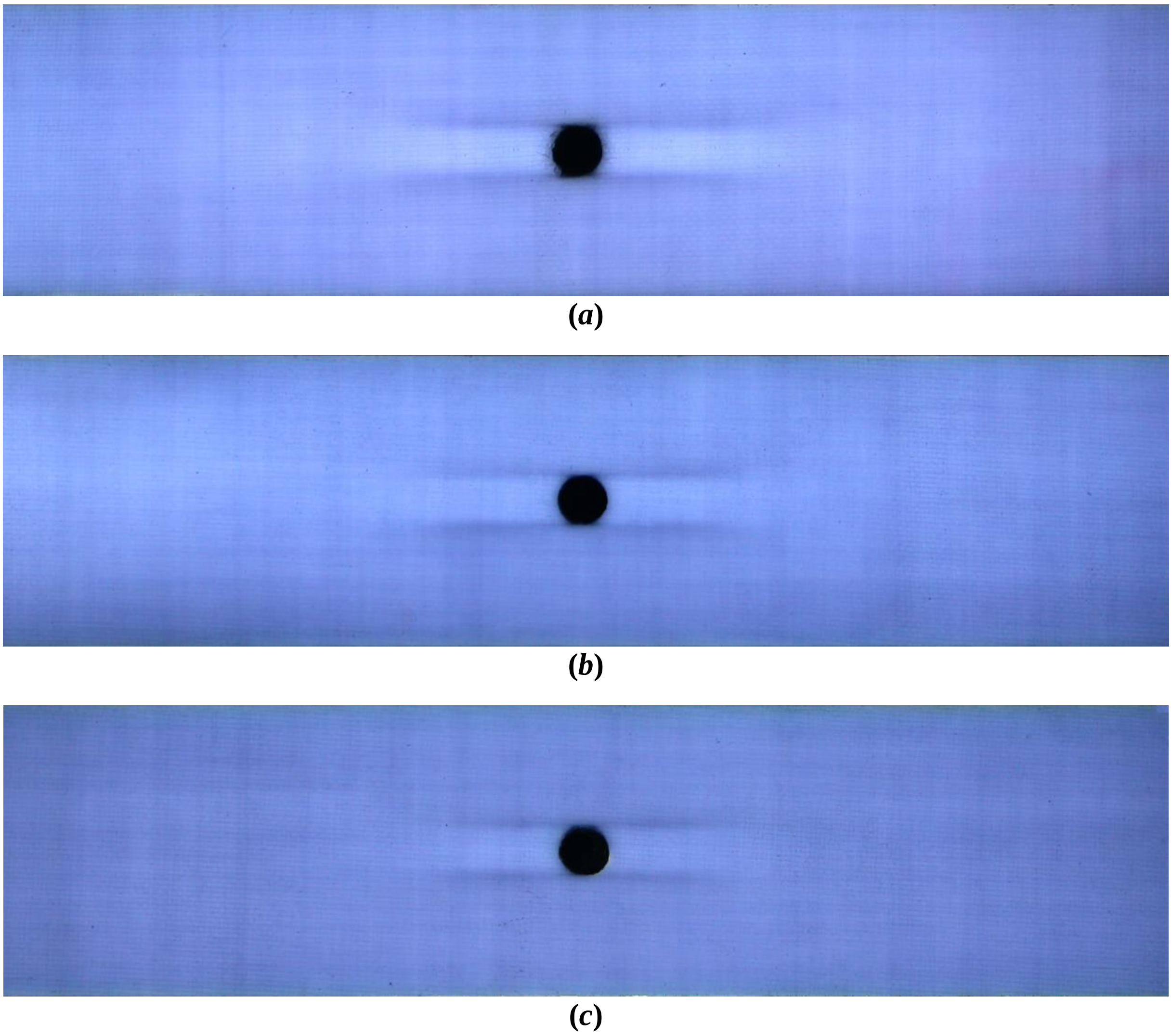


Figure 13; S2 FM94 GFRP CP$_1$ open hole tension specimen tested to (*a*) 95% of S_{OHT}, (*b*) 85% of S_{OHT} and (*c*) 75% of S_{OHT}.

3.2.3 Damage Progression in S2 FM94 GFRP Cross-Ply CP$_2$ Open Hole Tension Specimens

S2 FM94 GFRP cross-ply CP$_2$ open hole tension specimens were tested to eight different percentages of failure, 95%, 85%, 75%, 65%, 55%, 45%, 35% and 25%, respectively, to determine damage progression for this type of lay-up. No evident damage was seen to occur below 35% of the ultimate strength so therefore only the observation from that load level up are presented. The backlight observation results for each of these tests are presented in figures 14*a*, 14*b*, 14*c*, 14*d*, 14*e*, 14*f* and 14*g*, respectively.

This laminate has the same stacking sequence as the CP$_1$ laminate, however, but it has only four plies as opposed to 16 for the CP$_1$ laminate, and thus is significantly thinner. As with the

CP_1 laminate, damage in this laminate is characterised by matrix cracks adjacent to the hole in the 0° plies. Again, this damage appears as long shadows emanating from the edges of the hole in the direction of loading. However, for this laminate, in addition to the matrix cracks in the 0° plies, the formation of triangular regions of delamination can be seen from 65% of the ultimate strength upwards. These triangular regions of delamination are areas of shadow, which can be seen extending from near the tips of the matrix cracks in the 0° plies to the edge of the hole and can be seen growing bigger as the percentage of ultimate strength increases. Again, no other forms of damage are immediately evident in the backlight images of this laminate suggesting that the stress concentration due to the hole has been blunted by the matrix cracks in the 0° plies.

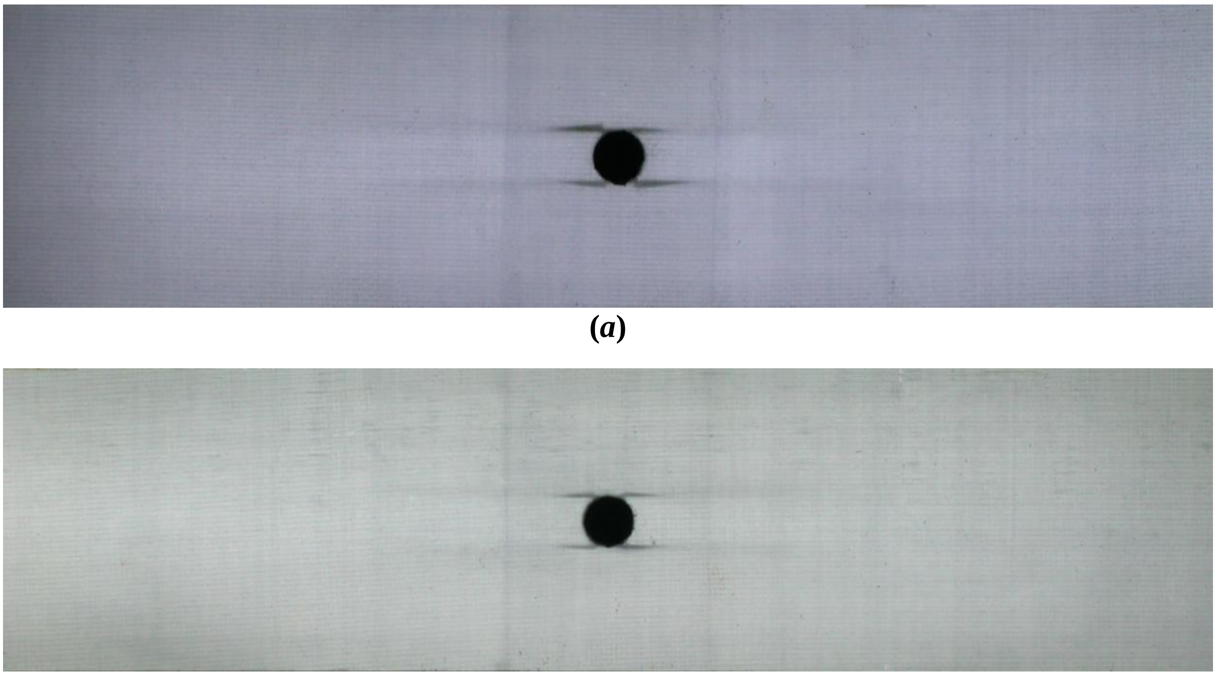
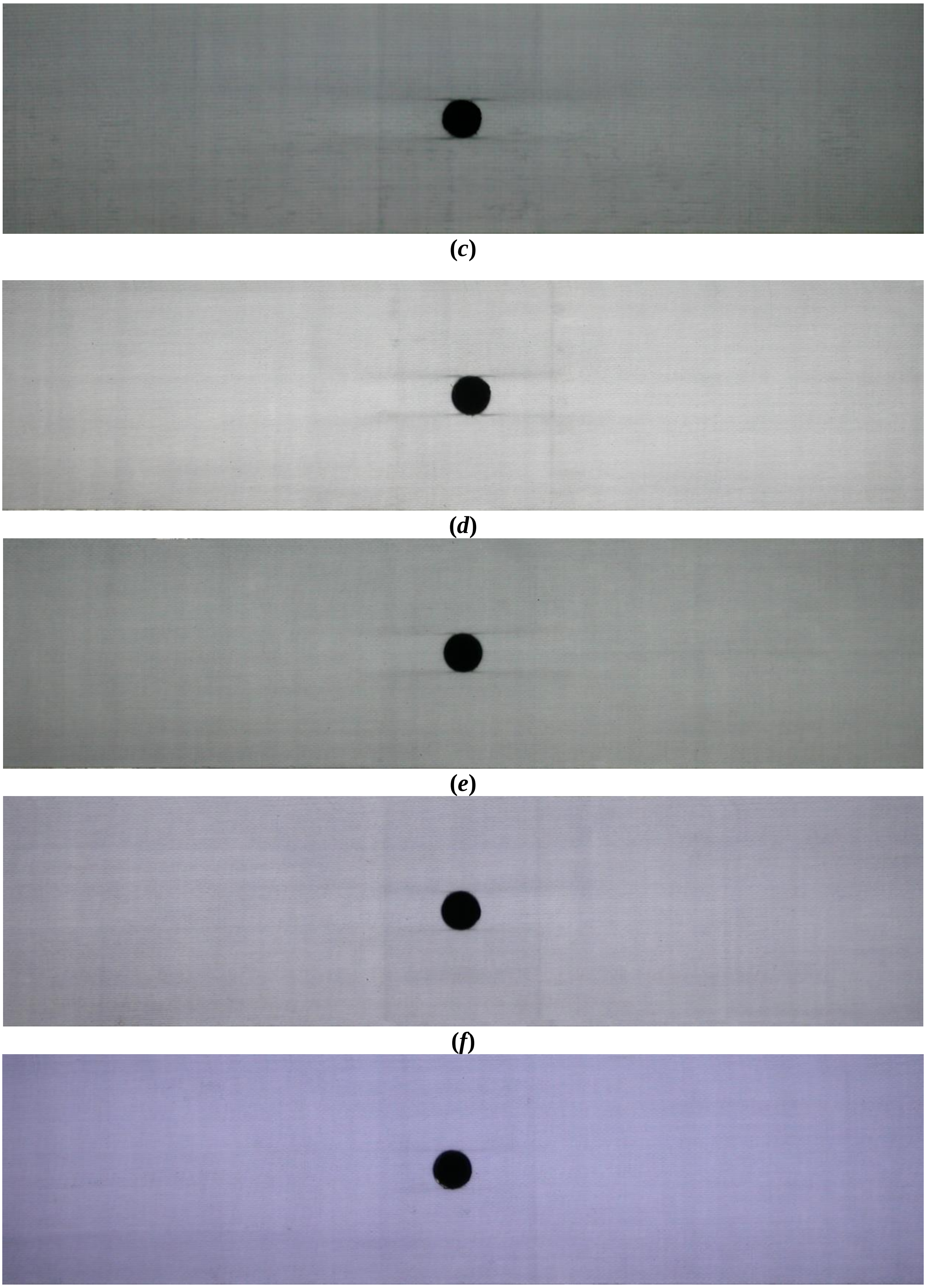


Figure 14, see next page for caption



(*c*)

(*d*)

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(*f*)

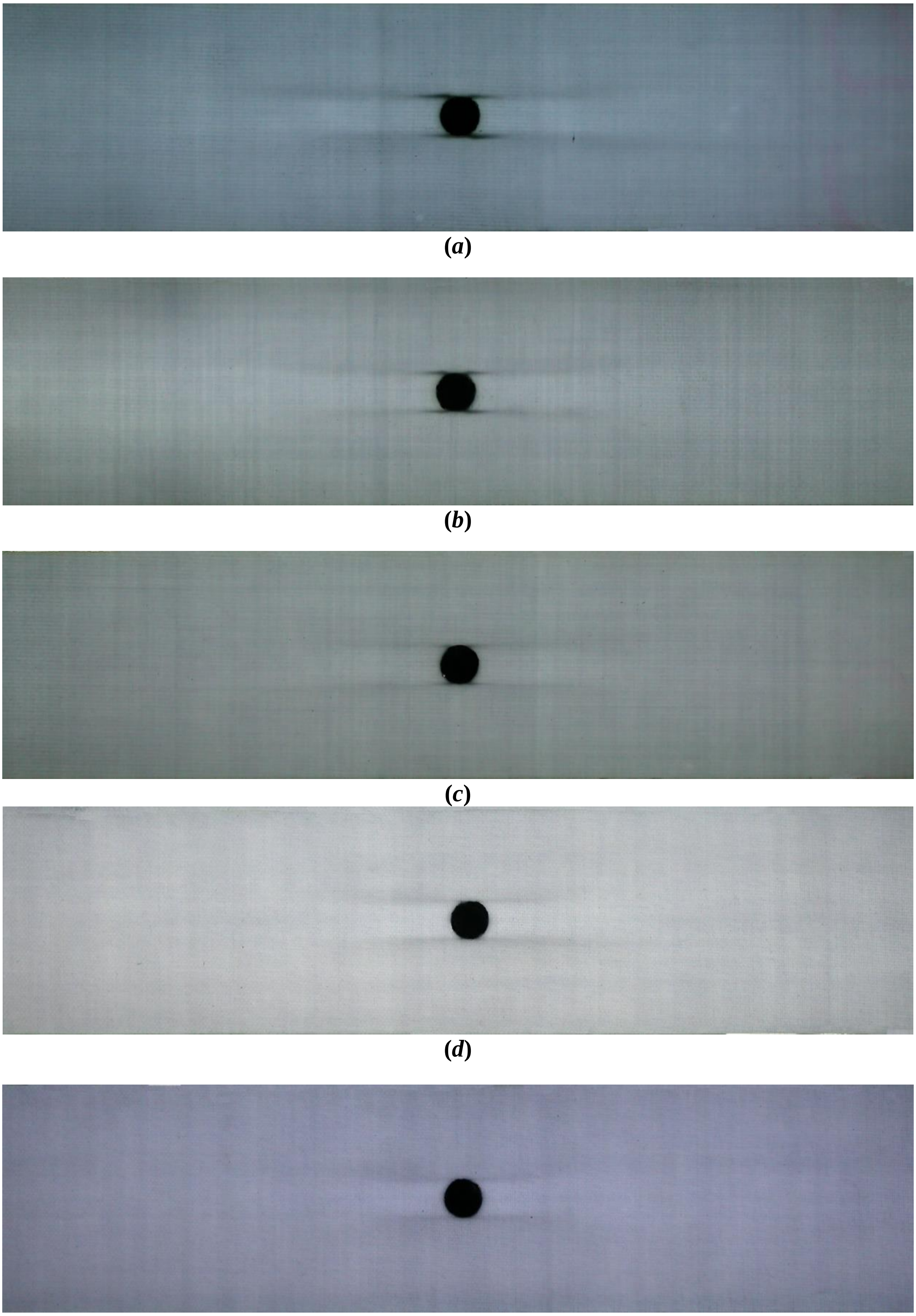
(*g*)

Figure 14; S2 FM94 GFRP CP$_2$ open hole tension specimen tested to (*a*) 95% of S_{OHT}, (*b*) 85% of S_{OHT}, (*c*) 75% of S_{OHT} (*d*) 65% of S_{OHT}, (*e*) 55% of S_{OHT}, (*f*) 45% of S_{OHT} and (*g*) 35% of S_{OHT}.

3.2.4 Damage Progression in S2 FM94 GFRP Cross-Ply CP_3 Open Hole Tension Specimens

S2 FM94 GFRP cross-ply CP_3 open hole tension specimens were tested to eight different percentages of failure, 95%, 85%, 75%, 65%, 55%, 45%, 35% and 25%, respectively, to determine damage progression for this type of lay-up. No evident damage was seen to occur below 35% of the ultimate strength so therefore only the observations from that load level up are presented. The backlight observation results for each of these tests are presented in figures 15*a*, 15*b*, 15*c*, 15*d*, 15*e*, 15*f* and 15*g*, respectively.

Again, this laminate has the same stacking sequence as the previous two cross-ply laminates examined. However, as this laminate consists of eight plies it has half the thickness of the CP_1 laminate and twice the thickness of the CP_2 laminate. As with the previous two laminates, damage in this laminate is characterised by matrix cracks adjacent to the hole in the 0° plies. The damage exhibited in this laminate is very similar to that observed in the CP_2 laminate, although it would appear that the triangular regions of delamination adjacent to the hole are not initiated until a higher percentage of ultimate load and do not appear to grow quite as large as those observed in the CP_2 laminate. Again, no other forms of damage are immediately evident in the backlight images of this laminate.



(*a*)

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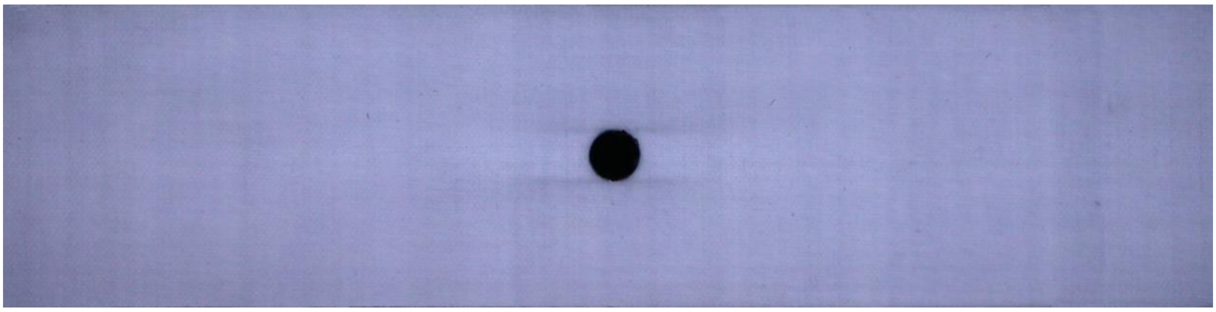
Figure 15, see next page for caption



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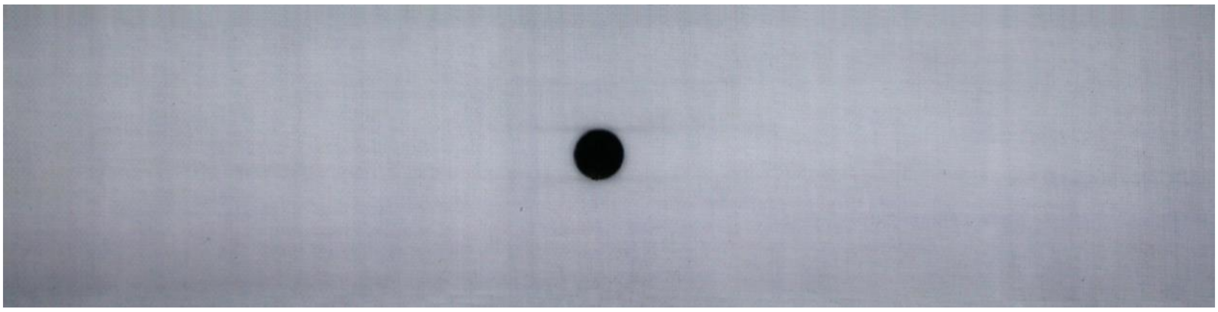


(*g*)

Figure 15; S2 FM94 GFRP CP$_3$ open hole tension specimen tested to (*a*) 95% of S_{OHT}, (*b*) 85% of S_{OHT}, (*c*) 75% of S_{OHT} (*d*) 65% of S_{OHT}, (*e*) 55% of S_{OHT}, (*f*) 45% of S_{OHT} and (*g*) 35% of S_{OHT}.

3.2.5 Damage Progression in S2 FM94 GFRP Cross-Ply CP$_4$ Open Hole Tension Specimens

S2 FM94 GFRP cross-ply CP$_4$ open hole tension specimens were tested to eight different percentages of failure, 95%, 85%, 75%, 65%, 55%, 45%, 35% and 25%, respectively, to determine damage progression for this type of lay-up. The backlight observation results for each of these tests are presented in figures 16*a*, 16*b*, 16*c*, 16*d*, 16*e*, 16*f*, 16*g* and 16*h*, respectively.

This laminate has a similar lay-up to the previously examined cross-ply laminates, i.e. the laminate is made up entirely of 0° and 90° plies, but it has a different stacking sequence. Whereas previously examined cross-ply laminates have an alternating stacking sequence for their constituent plies this laminate has a blocked stacking sequence. As such, the nature of the damage exhibited by this laminate is similar to that exhibited by previously examined cross-ply laminates, i.e. damage occurs in the form of matrix cracks adjacent to the hole in 0° plies accompanied by regions of triangular delamination in the vicinity of the hole. However, it can be clearly seen that the size of the damage zone in this laminate is much larger in this laminate than in any of the previous cross-ply laminates observed. In particular when one compares damage observed in the CP3 laminate, which has the same number of 0° and 90°

plies as this laminate, with the damage observed in the images shown in figure 16, the regions of triangular delamination are clearly significantly larger, particularly in the images taken at high percentage of the ultimate load. This clearly suggests that this sort of blocked stacking sequence laminate is more susceptible to damage initiation and growth than laminates with alternating stacking sequences.

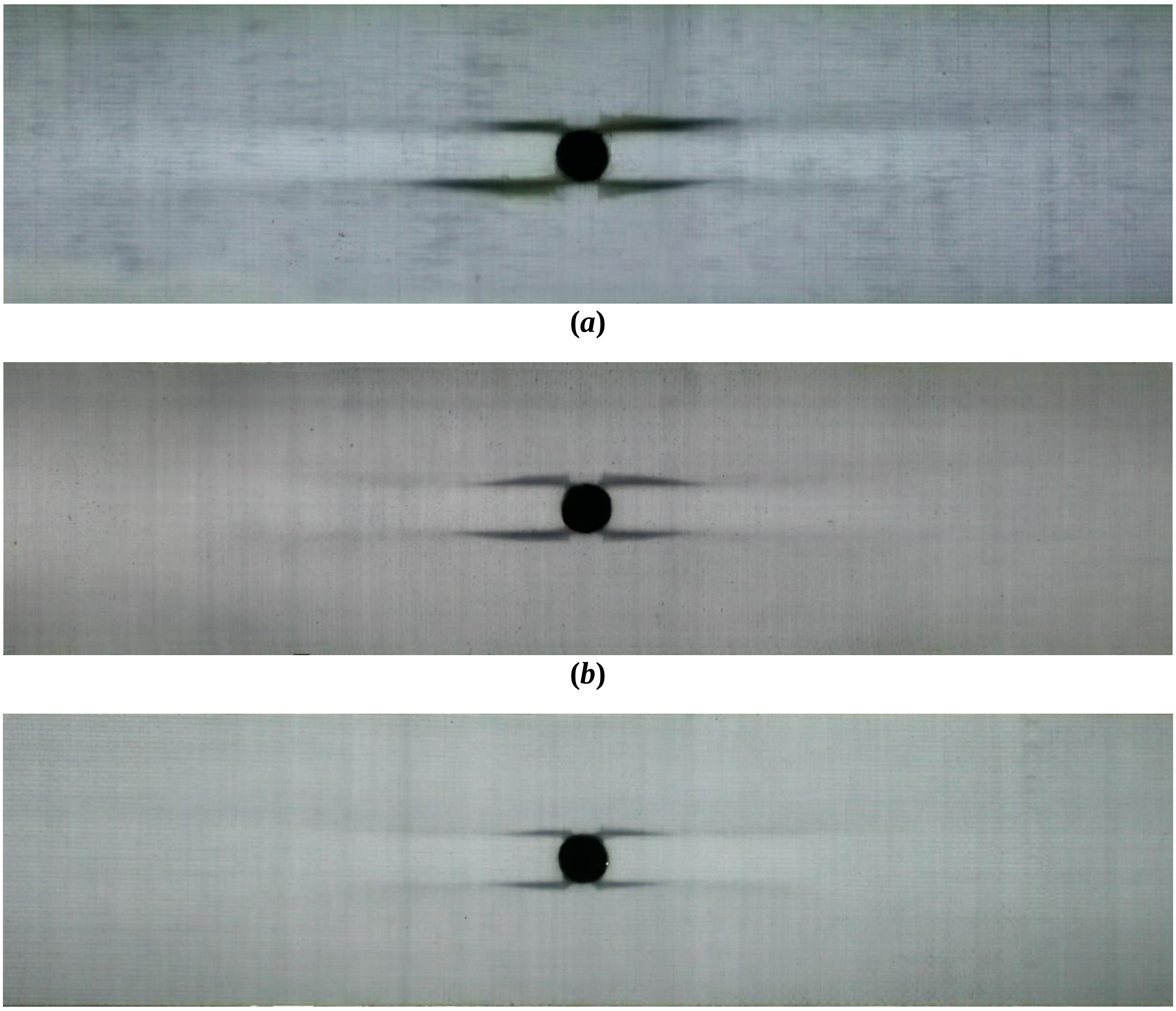
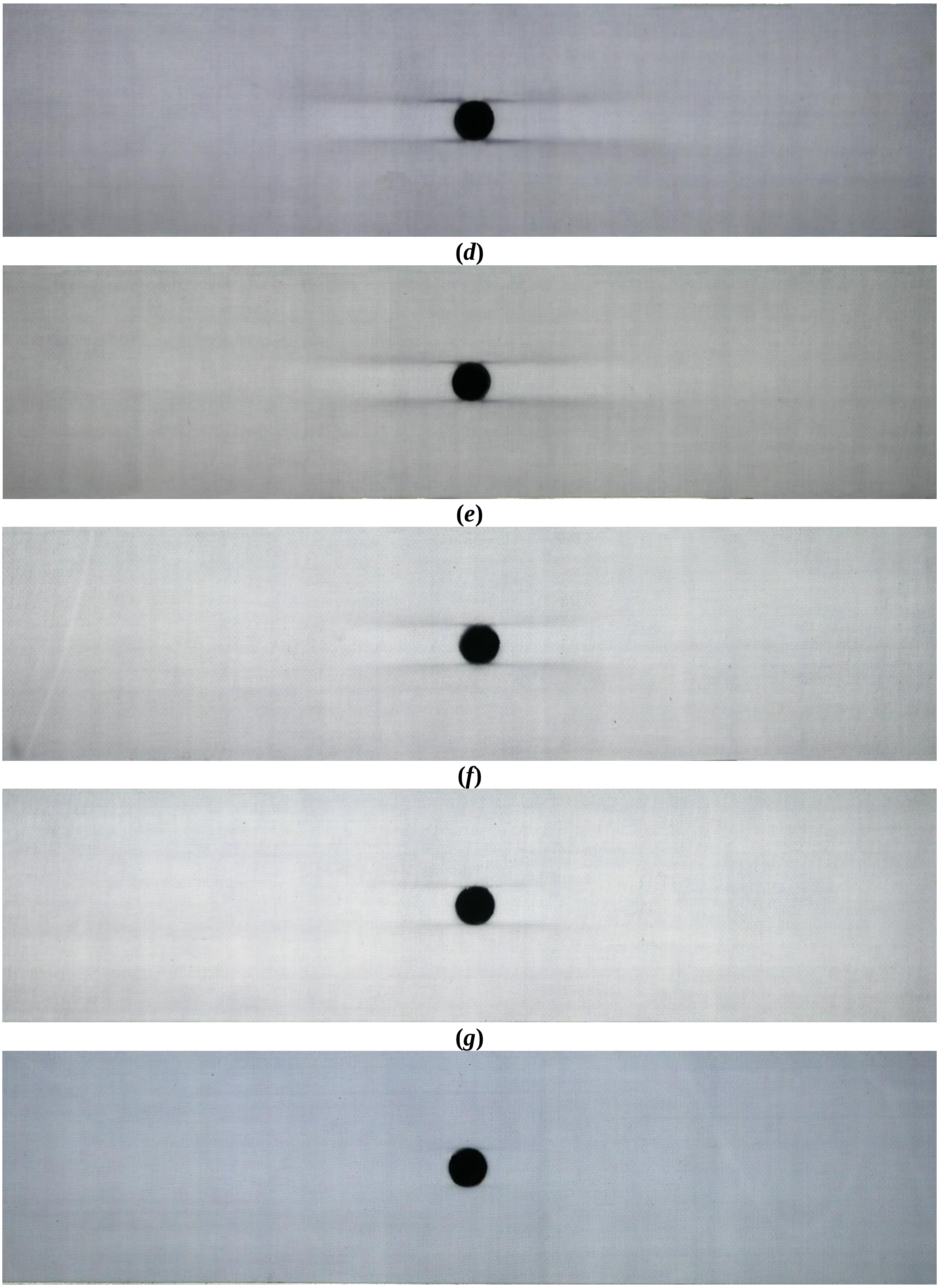

(*a*)
(*b*)
(*c*)

Figure 16, see next page for caption



(*d*)

(*e*)

(*f*)

(*g*)

(*h*)

Figure 16; S2 FM94 GFRP CP$_4$ open hole tension specimen tested to (*a*) 95% of S_{OHT}, (*b*) 85% of S_{OHT}, (*c*) 75% of S_{OHT} (*d*) 65% of S_{OHT}, (*e*) 55% of S_{OHT}, (*f*) 45% of S_{OHT}, (*g*) 35% of S_{OHT} and (*h*) 25% of S_{OHT}.

3.3 Factors That Effect Damage Growth and Initiation in Open Hole Tension Laminates

In is widely reported in the literature that notch tip damage prior to ultimate failure has a direct effect on the notched strength of composite laminates with a through thickness discontinuity [4-8]. This part of the report discusses some of the observed factors which affect damage initiation and growth in open-hole tension fibre reinforced composite laminates. For ease of discussion these factors are broken up into four different sub-parts: sub-part 3.3.1 discusses the effect which laminate lay-up has on damage initiation and growth, sub-part 3.3.2 discusses the hole size effect, sub-part 3.3.3 discusses the stacking sequence effect, and finally sub-part 3.3.4 discusses the thickness effect.

3.3.1 The Effect of Laminate Lay-up on Damage Initiation and Growth

Three different laminate lay-up types were examined in this study, namely, quasi-isotropic, zero-dominated and cross-ply. Whereas the quasi-isotropic and cross-ply lay-ups were examined for both material systems, the zero dominated lay-up was only examined for the HTA 6376 CFRP material. As damage characteristics exhibited by quasi-isotropic and cross-ply laminates for both material systems were similar, comparison will only be made between laminate lay-ups for the HTA 6376 CFRP material for ease of discussion. The three laminates to be discussed are the HTA 6376 CFRP quasi-isotropic, cross-ply CP_1 and zero dominated ZD_1 open-hole tension laminates. These three specific laminates were chosen as they all have roughly the same dimensions albeit that the ZD_1 laminate is slightly thicker than the other two as it has four more plies. It can clearly be seen from figure 4 that damage in the quasi-isotropic lay-up laminate is characterised by matrix cracks in the 90° and ±45° plies, accompanied by large areas of delamination emanating in a triangular shape from the hole to the edges of the laminate prior to failure. No significant matrix cracking in the 0° plies was observed, which is in contrast with the damage characteristics of the ZD1 and CP1 laminates, shown in figures 5 and 9 respectively, where the primary damage mechanism is matrix cracking in the 0° plies adjacent to the hole. From the radiographs of the ZD_1 and CP_1 laminates it appears that the matrix cracking in the 0° plies has the effect of blunting the stress concentration due to the hole in the laminate, as once they are initiated other forms of damage are restricted until just prior to ultimate failure. This theory is supported by the fact that the CP1 and ZD1 laminates have a much higher open hole tension strength (S_{OHT}) than the quasi-isotropic laminate, as can be seen in table 3. However, it is interesting to note that the quasi-isotropic laminate has higher normalised open-hole strength (S_{OHT}/S_{UN}) than the other two, perhaps making it a better choice for applications where structural strength and integrity needs to be maintained even if damaged.

Table 3 Comparison of HTA 6376 CFRP variable lay-up open hole strengths

Lay-up	S_{UN} (MPa)	S_{OHT} (MPa)	S_{OHT}/S_{UN} (%)
Quasi-Isotropic (QI)	**705**	**377**	**53.5**
Cross-Ply (CP_1)	**1112**	**480**	**43.2**
Zero-Dominated (ZD_1)	**1181**	**557**	**47.2**

3.3.2 The Effect of Hole Size on Damage Initiation and Growth

The effect of hole size on damage initiation and growth can be seen by examining the zero-dominated open hole tension laminates ZD_1, ZD_1 D8mm and ZD_1 D3mm. All the laminates have the same stacking sequence but have varying hole sizes, namely 6mm, 8mm and 3mm respectively. The widths of each laminate are such that a constant w/d ratio of 6 is maintained for each of the laminates. All laminates exhibit the typical damage characteristics of zero-dominated laminates, i.e. matrix cracks in the 0° plies on either side of the hole, accompanied by some minor matrix cracks in the 90° and ±45° plies. Comparing their radiographs (figures 5, 7 and 8) it can clearly be seen that the ZD_1 D3mm laminate has a larger damage zone and longer 0° plies matrix cracks, relative to hole size, than the other laminates prior to ultimate failure. In fact in general it would appear that damage prior to failure increases with decreasing hole size. This can possibly be explained by a stress distribution curve for a hole in an infinite isotropic plate obtained form Whitney and Nuismer [9], shown in Figure 17. The stress distributions for two hole sizes are examined: a 1 inch radius hole and a 0.1 inch radius hole. It can be seen that although the stress concentration factor for both holes is 3, as expected, the stress distribution slope is much steeper for the smaller hole. Whitney and Nuismer [9] reasoned that the notch size effect was due to this stress distribution phenomenon because the probability of a having a large flaw in the highly stressed region around the larger hole is greater, resulting in a lower average strength for a laminate with a large hole. This theory is supported by strength data presented for this set of laminates in Figure 18.

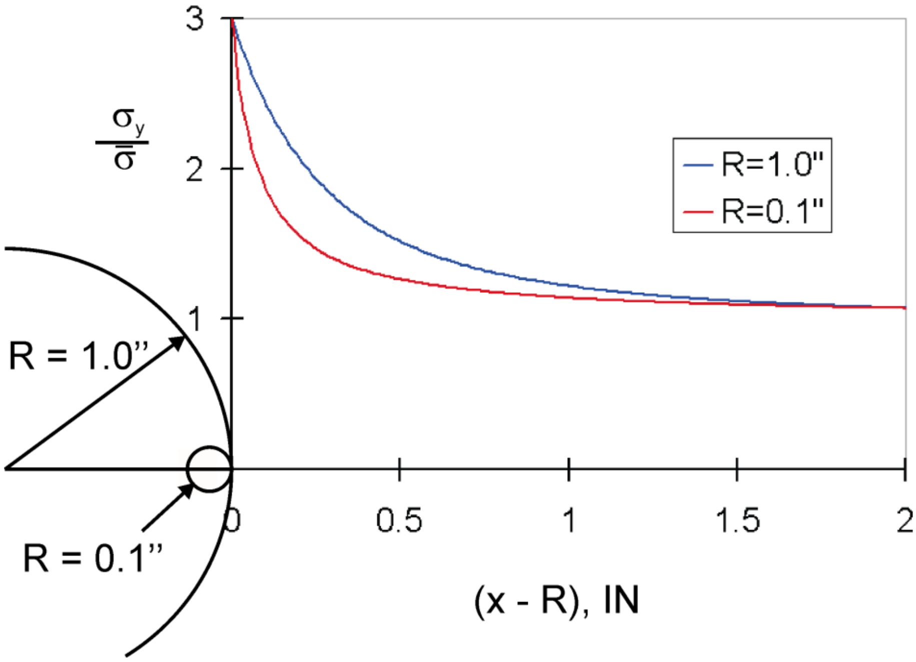


Figure 17 Stress distribution for a hole in an infinite plate (Whitney and Nuismer [9])

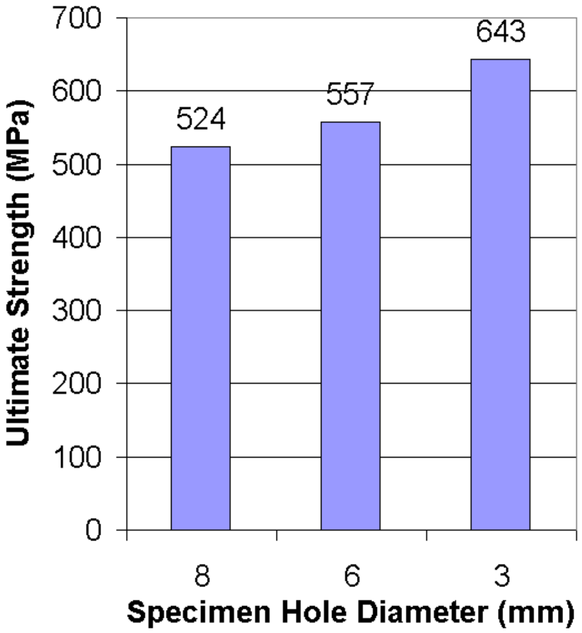


Figure 18, Change in the ultimate strength of HTA 6376 CFRP ZD1 open hole tension specimens of increasing hole diameters and a constant w/d ratio of 6

3.3.3 The Effect of Stacking Sequence on Damage Initiation and Growth

The effect of stacking sequence on Damage initiation and growth can be best seen by examining the cross-ply open hole tension laminates, CP3 and CP4. Both of these laminates have the same number of 0° and 90° plies each in their lay-up, however, CP_3 has an alternating type stacking sequence, whereas, CP_4 has a blocked type stacking sequence. Laminates of each type of lay-up were tested for both material systems studied in this test series. It was found that both material systems exhibited very similar damage characteristics for both lay-ups, therefore for ease of discussion only the results for the HTA 6376 CFRP material system will be discussed here. Examining the radiographs for both stacking sequences (figures 10 and 11) it can be seen that both laminate types exhibit the same cross-ply damage characteristics i.e. matrix cracks in the 0° and 90° plies accompanied by regions of triangular shaped delamination at the higher load levels. However, it is very evident that the CP_4 laminate is susceptible to much longer matrix cracks in the 0° plies, accompanied by larger regions of triangular delamination, and a greater volume of longer matrix cracks in the 90° plies than the CP_3 laminate. The extended length of the 0° ply matrix cracks adjacent to the hole has the effect of splitting the primary load carrying 0° plies into two unnotched regions and a central notched region, essentially completely blunting the stress concentration due to the hole and increasing the overall load carrying ability of the laminate. This statement is supported by the results for the open-hole tensile strengths of the CP_3 and CP_4 laminates shown in table 4, where it can be seen that the open hole tensile strength of the CP_4 laminate is just over 35% higher than that of CP_3.

Table 4, Comparison of HTA 6376 CFRP CP_3 and CP_4 open hole tensile strengths

Stacking Sequence	**S_{OHT} (MPa)**
CP_3 $[90/0]_{2s}$	**414**
CP_4 $[90_2/0_2]$	**560**

3.3.4 The Effect of Thickness on Damage Initiation and Growth

The effect of thickness on damage initiation and growth can be best seen by examining the cross-ply open hole laminates, CP_1, CP_2 and CP_3. All of these laminates have the same type of alternating stacking sequence. As no CP_2 laminate was examined for the HTA 6376 CFRP material the discussion is limited to the S2 FM94 material system, however, CP1 and CP3 laminates tested in both material systems showed very similar damage characteristics for each laminate type. Looking at the backlight images of the three different laminate types (figures 13 – 15) it is clear that all laminates exhibit typical damage characteristics of cross-ply laminates, however, the extent of damage prior to ultimate failure, in the form of matrix cracks in the zero degree plies, increases with decreasing thickness. This suggests that more notch blunting occurs in thinner laminates, which decreases the stress concentration due to the hole in the laminate. Examination of the open hole tensile strengths for each of these laminates, shown in figure 19, shows that strength decreases with increasing thickness indicating that additional notch blunting in thinner laminates helps to increase the laminate open hole tensile strength.

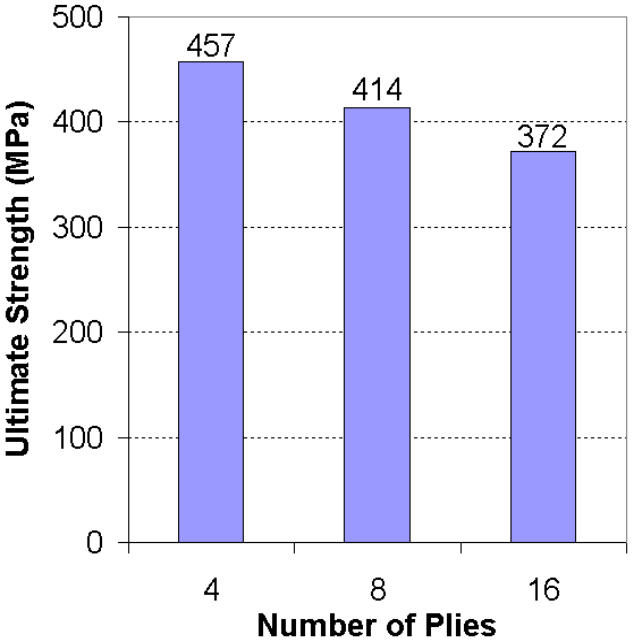


Figure 19 Change in the ultimate strength of S2 FM94 GFRP cross-ply open hole tension specimens with increasing thickness

4.0 Conclusions

From this study of damage initiation and growth in fibre reinforced composite open hole tension laminates, it can be concluded that the type and extent of damage growth in a notched laminate prior to failure has a significant influence on the notched failure strength of the laminate. Some of the factors found to have an effect on damage initiation and growth include laminate lay-up, the size of through thickness discontinuity, the stacking sequence of the laminate and the thickness of the laminate.

It is felt that more work should be carried out to determine the exact location in the thickness of the laminate of certain types of damage, as this information is hard to determine from methods such as penetrant radiography and backlight observation. A destructive inspection method such as laminate de-ply may be used in future to better determine the layer at which damage initiates, and between which plies delamination occurs. This information could be used to better understand the damage mechanisms taking place in the different types of laminate.

Finally, three dimensional finite element models should be used to try to determine the stress fields, which cause the particular damage mechanisms observed in this study for different laminates. Comparisons of numerical and experimental work may lead to better understanding of the complex damage and failure mechanisms which occur in fibre reinforced composite materials.

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