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The influence of stitching fibre and stitching density on the failure strains of CFRP fabrics

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Abstract

In this paper the results are described of an experimental programme in which the influence of stitching fibre and stitching density on the failure strains of carbon fibre fabric/epoxy laminates, impregnated by Resin Transfer Moulding (RTM), was investigated by carrying out static compression and tension tests. The results were compared to results of typical unidirectional prepreg specimens made in the autoclave.

The compression tests revealed that stitching did not result in a significant improvement of the allowable strain levels, due to the presence of circumferential roving reinforcements in the RTM fabric. Better results are expected without such reinforcements.

The compression after impact tests showed that failure strain levels for stitched and unstitched RTM specimens are almost equal to failure strain levels for autoclave specimens.

The tension tests revealed that high density stitching (10 stitches/cm^2) results in a severe reduction of the tension failure strains compared to unstitched values. A stitching density of 4 stitches/cm^2 will result in a small reduction of tension failure strain.

The stitching fibre type, Kevlar or Dyneema, has no influence on the failure strain levels.

1. Introduction

Impact damages can cause a severe reduction of the mechanical performance of a composite structure, especially when the structure is loaded in compression. To deal with this problem, designers limit the maximum strain level at Design Ultimate Load to values which can safely be reached in a damaged condition. Due to these strain level limitations, weight savings, which in theory could be achieved by using composites instead of metals, are seldom reached in practice.

One way to increase the maximum allowable strain level at Design Ultimate Load is to increase the damage tolerance of the composite materials used. This can be achieved by adding "through the thickness" fibres to the composite, resulting in a 3-D composite. The "through the thickness" fibres prevent delaminations, caused by impact, from buckling when the structure is loaded in compression [1,2].

To investigate the influence of stitching fibre and stitching density on the failure strains of carbon fibre fabric / epoxy laminates, impregnated by Resin Transfer Moulding (RTM), an experimental programme was carried out. The results were compared to results of typical unidirectional prepreg specimens made in the autoclave. The programme was carried out by NLR in collaboration with the Australian Research Centre for Advanced Composite Structures (CRC-ACS), under a contract awarded by the Netherlands Agency for Aerospace Programmes (NIVR). The CRC-ACS produced the stitched preforms that were needed for the fabrication of flat plates and performed open hole fatigue Cooperative tests. The NLR fabricated the flat plates, machined the flat plates to specimens and carried out the static test programme.

The results of the open hole fatigue tests are reported in [3]. This paper presents the results of the static test program. The test programme revealed that the stiffness of the RTM and autoclave specimens were nearly the same. This means that the influence of the stitching density and stitching fibre on the failure strain can also be interpreted as the influence of the stitching density and stitching fibre on the failure stress.

2. Plate configurations

A number of flat plates were fabricated, eight by RTM and two by autoclave processing. After curing, these plates were machined to the dimensions of the test specimens. The plates differed from each other by stitching density (0 stitches/cm^2, 4 stitches/cm^2 and 10 stitches/cm^2), materials used (unidirectional carbon fabric / epoxy for the RTM plates and unidirectional carbon tape/epoxy prepreg for the autoclave plates), stitching fibre (Kevlar and Dyneema) and by laminate lay-up (“soft” laminates with a high percentage of 45^0 layers and "hard" 0^0 layer, dominated laminates (see table 1)).

The thickness of one layer RTM fabric did not correspond to the thickness of one layer unidirectional prepreg tape. To make the RTM plates as compatible as possible to the autoclave plates, the number of prepreg layers for the autoclave specimens was chosen in a way that the same amount of fibres was used, as close as possible, in the RTM plates as in the autoclave plates while maintaining laminate symmetry. Therefore, one prepreg layer was added to autoclave laminate no. 4 to make it compatible with RTM laminate no. 2 and two prepreg layers were added to autoclave laminate no. 3 to make it compatible to RTM laminate no. 1 (only one layer was needed for compatibility of the amount of fibres, however, because of symmetry, two layers had to be added). After curing all plates were inspected by C-scan.

3. Test specimens

The cured flat plates were machined to the dimensions of the following specimens for the static test program (see fig. 1): tension specimens, short block compression specimens, compression after impact specimens, open hole compression specimens and open hole tension specimens. Three specimens were made for each test configuration.

4. Test programme

A test programme was composed to obtain a global characterization of the mechanical properties of the materials used. The test programme can be divided into two areas: compression and tension tests.

The compression tests were subdivided into short block compression tests, open hole compression and compression after impact tests. The short block compression tests were used as a reference to determine the reduction in failure strain caused by an impact or an open hole. The compression after impact and open hole compression tests were used to evaluate the damage tolerance behaviour of the materials used.

The tension tests were subdivided into standard tension and open hole tension tests. The standard tension tests were used as a reference to determine the reduction in tension failure strain caused by an open hole (which is considered as the most severe type of damage in tension loaded structures).

All tests were carried out at ambient conditions. The tests were performed on a mechanically driven static test machine. All tests were carried out under displacement control with a velocity of 1.0 mm\min.

To avoid buckling of the open hole compression and compression after impact specimens, an anti-buckling guide (with a window of 125 mm x 60 mm) was used during the tests of these specimens. During the tests, failure loads and strains were recorded. To check the validity of the compression after impact and open hole compression tests, out of plane deformations of the specimens were recorded also during these tests.

5. Impact tests

Before being tested, the compression after impact specimens were impacted. To apply these impacts an instrumented impact tower was used. During impact the specimens were clamped in a frame with a window of 75 mm x 125 mm. The impacts were applied by a steel spherical tub with a diameter of 0.5" at a velocity of 3.96 m/s.

The Barely Visible Impact Damage (BVID) was considered as the most severe impact damage for a structure, since a structure with a BVID still has to be able to withstand Design Ultimate Load (DUL). To determine the BVID energy level, a number of impact tests were conducted on spare specimens of configuration no. 2.3. These impact tests showed that the BVID energy level for these plates was 18 Joule. Therefore it was decided to impact all CAI specimens with this 18 Joule energy level, resulting in indentations between 0.25 mm to 0.55 mm.

6. Test results and discussion

6.1 Compression test results

Figure 2 shows the average compression, open hole compression and compression after impact test results, based on the results of three specimens of the same configuration. From this figure the following observations can be made:

1) The short block compression failure strains of the RTM specimens (configuration 1 and 2) are much lower than the short block compression failure strains of the autoclave specimens (configuration 3 and 4). This can be explained partly by the fact that the RTM specimens were made of fabric, whereas the autoclave specimens were made of unidirectional tape. However, the main reason for the limited failure strains of the RTM specimens must be accredited to the type of fabric that was used. In the fabric used, a number of rovings are configured with a circumferential reinforcement. Because of this reinforcement, these rovings will not be compacted when the RTM mould is closed and therefore the permeability of the fabric will be enhanced. However, it will also

introduce resin pockets in the cured laminate. These resin pockets lead to instability when the laminate is loaded in compression and will cause a severe reduction in compression failure strain [4].

2) The autoclave specimens (configuration 3 and 4) show a tremendous reduction in failure strain level due to an open hole or when damaged by impact.
3) The RTM specimens (configuration 1 and 2) show a much smaller reduction in failure strain level due to an open hole or when damaged by impact.
4) RTM specimens with high density stitching (configuration 1.3 and 2.3) show higher compression after impact failure strains than RTM specimens without stitches (configuration 1.1 and 2.1) and medium density stitching (configuration 1.2 and 2.2).
5) Compression after impact failure strain levels of the RTM specimens are nearly the same as the compression after impact failure strain levels of the autoclave specimens, when comparing soft laminates 1 and 3, and hard laminates 2 and 4.
6) The compression after impact failure strain level of the unstitched RTM specimens (configuration 1.1 and 2.1) is almost equal to the compression after impact failure strain level of the stitched RTM specimens (configuration 1.2, 1.3 and 1.5 and configuration 2.2, 2.3 and 2.5).
   Although the motivation to use a stitching fibre to improve damage tolerance was not clearly substantiated, stitching may still be a viable concept to reduce fabrication costs. A stitching fibre facilitates handling of a preform since the stitching of fibres stabilizes the preform. Tooling costs will be reduced because the stitching of fibres compact the preform and therefore the loads required to close the mould will be limited. The assembly costs will be reduced, because the amount of fasteners needed for assembly will be reduced.
7) The stitching fibre type has no effect on the failure strain (compare configuration 1.2 with 1.5 and configuration 2.2 with 2.5).

6.2 Tension test results

Figure 3 shows the average tension and open hole tension test results, based on the results of three specimens of the same configuration. From this figure the following observations can be made:

1) The failure strains of the tension specimens made by RTM (configurations 1 and 2 except configuration 2.3 with 10 stitches/cm^2) are close to the failure strains of the tension specimens made in the autoclave (specimens 3 and 4).
2) The RTM specimens (configurations 1 and 2) show similar open hole failure strain levels as the autoclave specimens (configurations 3 and 4).
3) Specimens with laminate configuration 2.3 (Kevlar stitching fibre and 10 stitches/cm^2) show a severe decrease in tension failure strain, due to the high stitching density in these specimens.
4) The stitching fibre type (Kevlar or Dyneema) has no effect on both the tension and the open hole tension failure strain (compare configuration 1.3 with 1.5 and configuration 2.2 with 2.5).

7. Conclusions

An experimental static test program was carried out to investigate the influence of stitching fibre and stitching density on the mechanical performance of CFRP fabrics by testing specimens statically in tension and compression. The program showed that for the RTM fabric specimens with a circumferential roving reinforcement, stitching did not result in a significant improvement of the allowable strain levels at Design Ultimate Load. However, compression after impact tests showed that the reduction in compression failure strain due to an impact is much smaller for the RTM specimens than for the autoclave specimens while the compression after impact failure strain levels for these materials are almost equal.

This means that when the compression failure strain in undamaged condition can be improved (by using fabrics without circumferential roving reinforcements) while the reduction in compression failure strain due to damage remains in the same order of magnitude, then the allowable compression strain levels at Design Ultimate Load will increase. As a result, the allowable strain levels at Design Ultimate Load for RTM composites may reach beyond those of the traditional autoclave prepreg tape composites.

In the framework of a follow-on program, unidirectional CFRP fabric without circumferential roving reinforcement was impregnated with epoxy resin by RTM. Compression tests on specimens of this material revealed that the failure strain in undamaged condition was doubled in comparison to the failure strains of the RTM specimens with circumferential roving reinforcement [5]. In future work the damage tolerance behaviour of this fabric will be investigated further.

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Config:	Material:	**Fabrication process:**	**Stitch density and stitching fibre:**	**Lay-up no.:**
1.1	1	RTM	0	1
1.2	1	RTM	4 st/cm^2 Stitching fibre: 2x40 tex Kevlar	1
1.3	1	RTM	10 st/cm^2 Stitching fibre: 2x40 tex Kevlar	1
1.5	1	RTM	4 st/cm^2 Stitching fibre: 3x16.5 tex Dyneema	1
2.1	1	RTM	0	2
2.2	1	RTM	4 st/cm^2 Stitching fibre: 2x40 tex Kevlar	2
2.3	1	RTM	10 st/cm^2 Stitching fibre: 2x40 tex Kevlar	2
2.5	1	RTM	4 st/cm^2 Stitching fibre: 3x16.5 tex Dyneema	2
3.1	2	Autoclave curing	0	3
4.1	2	Autoclave curing	0	4
Material 1:		Unidirectional carbon fabric GU230-E01-100, HTA fibre, epoxy resin LY5052 and Hardener HY5052		
Material 2:		**Unidirectional carbon prepreg tape, HTA fibre, epoxy resin 6376**		
Lay-up 1: (soft laminate)		[45,-45,45,0,-45,90,45,-45,0,-45,45,90,-45,0,45,-45,45] $E_{1compression}$ = 34532 N/mm^2		
Lay-up 2: (hard laminate)		[45,0,-45,0,45,90,0,-45,0,-45,0,90,45,0,-45,0,45] $E_{1compression}$ = 51782 N/mm^2		
Lay-up 3: (soft laminate)		[45,-45,45,0,-45,90,45,-45,45,0,45,-45,45,90,-45,0,45,-45,45] $E_{1compression}$ = 34898 N/mm^2		
Lay-up 4: (hard laminate)		[45.0,-45,0,45,90,0,-45,0,0,-45,0,90,45,0,-45,0,45] $E_{1compression}$ = 59953 N/mm^2		

** The compression modulus was determined by taking the tangent of the load-strain curves ,measured during the short block compression tests, divided by the area of the specimens. Fibre volume fractions of the plates was 55%.

Table 1: Plate configurations and laminates used

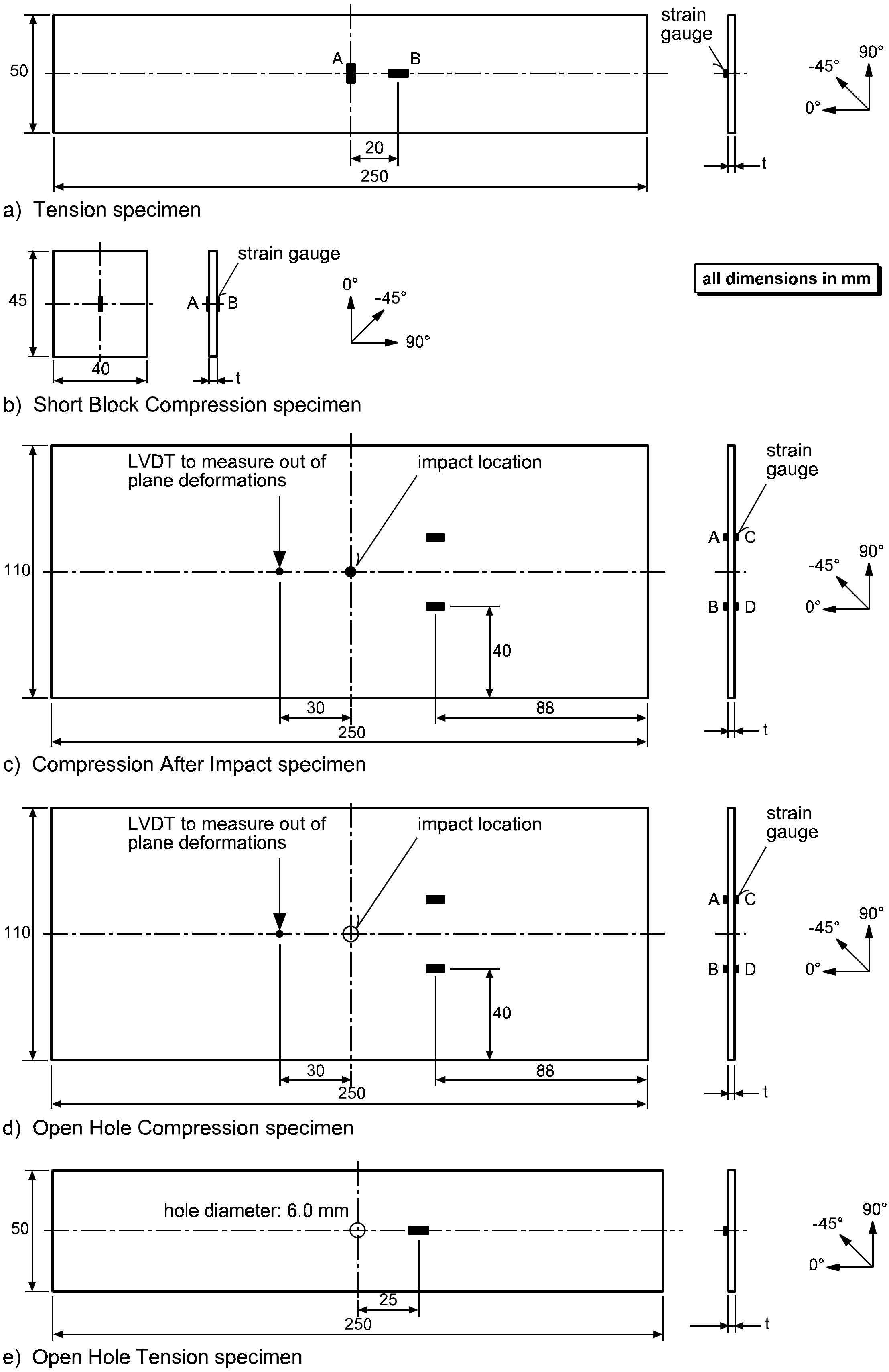

Fig. 1 Specimen definition

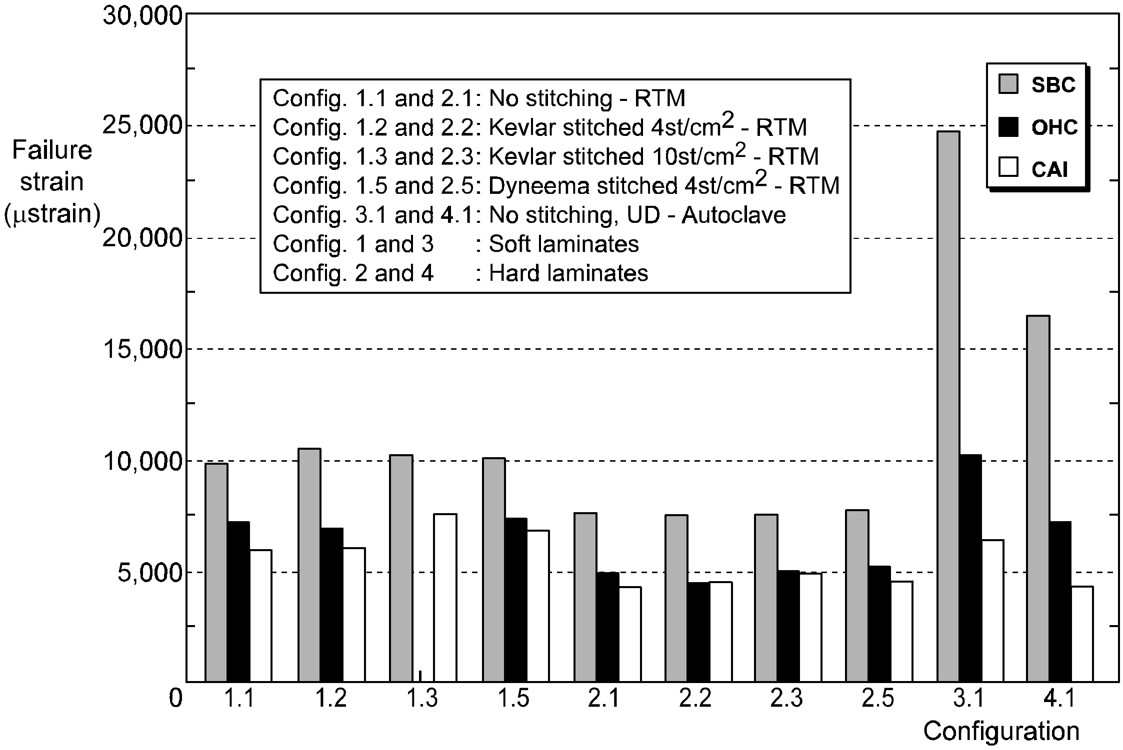

Fig. 2 Influence of stitching density, stitching fibre and laminate on the compression behaviour

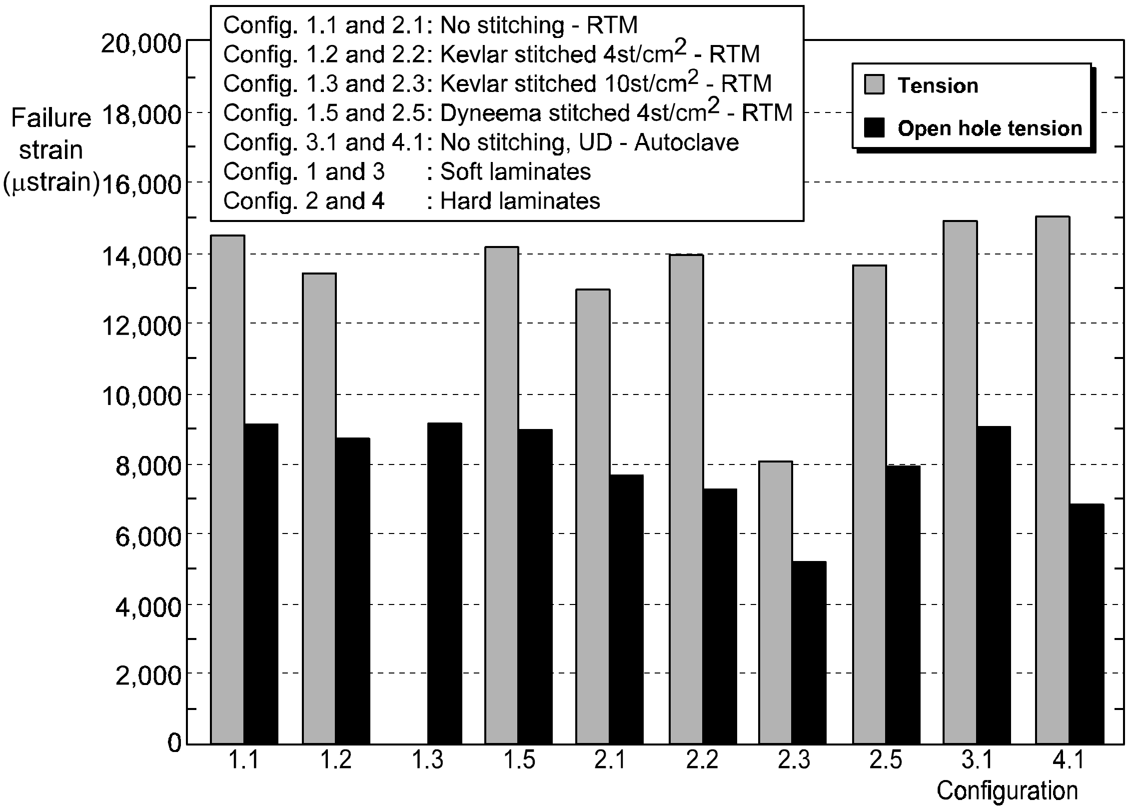

Fig. 3 Influence of stitching density and stitching fibre on tension behaviour