IMPACT AND POST-IMPACT PROPERTIES OF CARBON FIBRE NON CRIMP FABRIC COMPOSITES

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ABSTRACT

Although non-crimp fabric composites (NCFCs) have become an important and valuable material for many composite applications, some elements of their mechanical behaviour are still poorly understood and there is a need for additional research. In this study, the impact and post-impact static and dynamic properties of a carbon fibre/epoxy NCFC are determined and compared to those of a carbon fibre/epoxy woven fabric composite, for two impact energies. The projected damage area after impact was measured using the C-scan technique. For the NCFC this area is larger than that for the WFC for both impact energies. Impacted samples were subjected to static tensile tests and tensile-tensile fatigue tests. It was found that a relatively low energy impact has a significant negative influence on the residual properties in both static and dynamic tests, in the fibre direction as well as in the matrix dominated direction. Mostly, the higher energy impact caused a larger reduction in properties than the lower energy impact, although in some cases, no significant difference in the results was found between samples impacted with these two energies.

1. INTRODUCTION

Composite materials have a high in-plane stiffness and strength-to-weight ratio, making them attractive materials for use in numerous transport applications, like cars and airplanes. One type of composites in particular, the non-crimp fabric composites , seems quite promising in this field, as non crimp fabrics (NCF) are nearly as easy to handle as woven fabrics and have a reasonable drapeability, while lacking the rather large amount of fibre crimp often present in woven fabrics. This combination makes it possible to reduce the production cost and maintain excellent properties.

In the recent past, extensive research has been conducted concerning non-crimp fabrics and their composites. Asp investigated the influence of the stitching parameters on the mechanical properties of UD NCF composites for 10 different stitching patterns [1]. He could find only negligible differences in the tensile strength and stiffness. Concerning the fatigue properties, he concluded that although the general performance of NCF composites in fatigue was better than that of UD prepreg composites, the different stitching patterns did not lead to significantly different fatigue properties.

The present authors have recently published a series of 6 papers, covering a wide variety of properties of both dry NCF fabrics and their composites [2-7]. In parts 1,2,3 and 5 of this series [2-4, 6], a comprehensive study of the behaviour of several dry carbon fibre non crimp fabrics can be found, including modelling of the internal geometry of undeformed, compressed and sheared fabrics, and characterisation of the behaviour of the fabrics in tension, shear, bending, compression and friction. Part 4 and 6 of the series [5, 7] treat the general mechanical properties of several kinds of composites made from the fabrics discussed in the previous parts, as well as the damage initiation and development during static tensile testing and the characterisation of the fatigue behaviour at low loads.

Most of the research done concerns the in-plane properties of NCF composites. However, it is not unlikely that a composite part will encounter one or more significant out-of-plane loads during it's lifetime: a car can be hit by a stone, an airplane can suffer from an impact by birds or hail stones etc. Therefore, it is important to know if, and how, the impact and post-impact properties of NCF composites differ from other types of composites.

In [8], Ding investigated the effect of impact events with varying energy on the strength of a plain weave carbon epoxy composite. He concluded that below a certain threshold for the impact energy, there was no significant influence of the impact damage on the tensile strength of the material. As the impact energy was increased above the threshold value, a rather sharp decline of the residual strength was noted. Cantwell found a similar behaviour for a UD cross-ply carbon/epoxy material [9], although the decline in strength after the threshold energy was less steep.

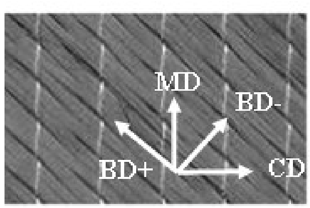
Ding also studied the influence of an impact on the tensile fatigue properties [8]. He found that an impact damaged sample will degrade faster than a non-impacted sample, and that the fatigue life of the former is consequently lower.

In the present paper, the impact properties of a carbon fibre/epoxy NCF composite are compared to those of a carbon fibre/ epoxy woven fabric composite (WFC). The absorbed energy and the projected damage area have been investigated as a function of the impact energy. The influence of the impact damage on the residual static tensile properties and the residual tensile fatigue properties was determined for two impact energy levels.

2. MATERIALS AND METHODS

2.1 Materials and production

A ±45° biaxial carbon fibre NCF and a carbon fibre twill weave were used for this study. The materials are shown in figure 1. The fabric has an areal density of 540 g/m² and is prelaminated with an epoxy resin layer. For this study, both a (+45,-45) and a (-45,+45) fabric were used, to allow for the production of a fully symmetrical laminate in which also the direction of the stitching is aligned. The twill weave has an areal density of 380 g/m² and is supplied in the form of prepregs. The epoxy resin used is the same for both types of reinforcement.



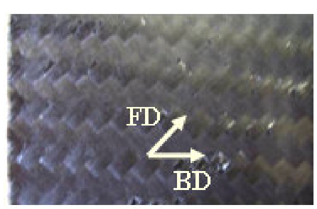


Fig. 1: materials and testing directions

Composite plates were produced using a modified resin film infusion process. In a first step, prepregs were made from the prelaminated NCF material. In the second step, several prepreg layers were stacked symmetrically to produce the final laminate. The processing conditions for the NCF prepregging step and the actual plate production step can be found in table 1.

Table 1: Processing conditions for the production of the composite plates

Step	Time (min)	Temp. (°C)	Vacuum (MPa)
1	5	90	-0.095
2	30	90	-0.095
	60	130	-0.095

For the impact and post-impact tests, plates with an average thickness of 2.1 mm for the NCFC and 1.9 mm for the WFC were made. To obtain an average fibre volume fraction of 58 % in both materials, 4 prepreg layers were used for the NCF composite (NCFC) plates (lay up: $[-45,+45]_{2s}$), and 5 layers for the woven fabric composite plates (WFC).
The nomenclature for the sample directions used for the mechanical tests is illustrated in figure 1. In the NCF material, MD and CD stand for machine and cross direction respectively, BD+ is one of the two fibre directions, oriented so that the fibres in the outer layer of the sample are parallel to the loading direction (i.e. the -45° direction), and BD- is perpendicular to BD+ (i. e. the +45° direction). FD and BD denote fibre and bias direction in the woven fabric composite.
For the impact and post-impact tests in this study, samples were cut in the following directions: BD+ and CD (NCFC) and FD and BD (WFC). The dimensions of the samples were 280*50 mm². Composite end tabs were glued onto the samples, giving a gauge length of approximately 200 mm.
For the interlaminar fracture toughness tests, the number of prepregs in a plate was doubled, to obtain thicker samples. A thin aluminium foil coated with a release agent was inserted in the middle to act as a crack/delamination initiator. For the mode I tests, aluminium load transfer blocks were glued to the end of the sample.

2.2 Experimental methods

Interlaminar fracture toughness tests

Double cantilever beam (DCB) and end notch flexural (ENF) tests were done to determine the mode I and mode II interlaminar fracture toughness.
The DCB tests were done in accordance with the ASTM D5528 standard. The mode I interlaminar fracture toughness values for initiation and propagation were calculated from the measured forces, crack opening displacements and crack lengths using the modified beam theory. For the ENF tests the method outlined by Carlsson in [10] was used. During this type of test there is a high risk of instable crack growth, resulting in only one data point per test. To avoid measuring a combination of initiation and propagation values in such cases, Carlsson recommended that the initiation of a crack from the foil be done manually before starting the test. This recommendation was followed in this work, so only values for the mode II propagation toughness were obtained.

Impact tests and damage analysis

The impact tests were done using an instrumented drop weight impact tester with a square clamping opening of 40 x 40 mm². Two different impact energies were used: 3.5 and 7 J. All tests were done with a semi-hemispherical impact head with a diameter of 13mm. The force acting on the impact head was measured by a load cell, and the displacement of the head was registered by means of a reflected-laser beam optical

device. From these displacements, the initial speed just before the impact and the final speed just after impact can be determined, and hence the difference in kinetic energy before and after the impact, referred to as the 'absorbed energy'.
Damage investigation was done by ultrasonic C-scanning. Undamaged areas will appear black or dark grey in the resulting image, areas with delaminations will be white or light grey. By applying a threshold value for the grey level, the delamination area can be determined. However, it is important to note that in this way not the sum of the delaminations between the different layers of the material is determined, but the area of the *projection* in the same plane of all the delaminations in the sample.

Post-impact static and dynamic tensile tests

Post-impact tensile tests were done on samples impacted with an energy of 3.5 and 7 J. An Instron 1196 tensile machine was used for the static tests, and the test speed was 1 mm/min.
The tensile-tensile fatigue tests were done in load control mode on a vertical 160kN Schenck machine. A test frequency of 6 Hz was adopted for all tests. The R value (ratio of minimum stress over maximum stress) was 0.1. The maximum stress for the fatigue tests was chosen as the stress level corresponding to a fatigue life of about 10^6 cycles for an undamaged sample.

3. RESULTS AND DISCUSSION

3.1 Interlaminar fracture toughness tests

Mode I interlaminar fracture toughness

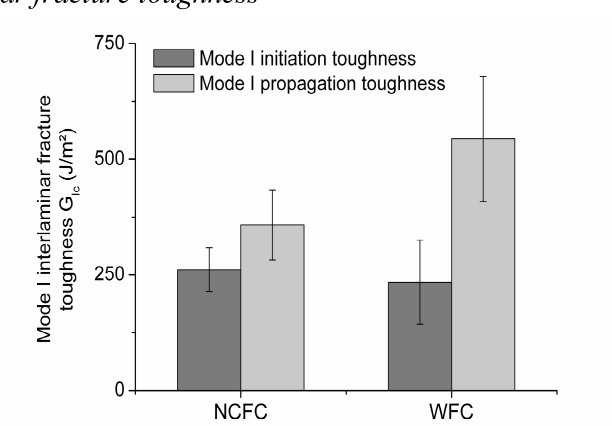


Fig. 2: Mode I interlaminar fracture toughness test results for the NCFC and the WFC

The mode I interlaminar fracture toughness values (*mode I critical energy release rate*, G_{Ic}) for the NCFC and the WFC are shown in the graph in figure 2. Both the initiation and the propagation toughness is given. No significant difference can be found between the initiation values for the two materials. This is not surprising, as initiation of a crack is mainly determined by the resin matrix properties, and not by the reinforcement architecture. However, there is a pronounced difference in the propagation values of G_{Ic}. The toughness of the WFC is about 50% higher than that of the NCFC. This can be explained by the nature of the reinforcement: in the NCFC, the crack will follow the interface between two quasi-straight fibre layers, much like in a UD laminate, and the crack path will therefore be approximately linear. In the WFC, however, a crack following the matrix/reinforcement interface will be forced to follow a wavy crack path, as the crack must change its direction to follow the undulations of the fibre bundles in the woven fabric. A wavy crack path will have a longer effective crack length than a straight crack, and thus a higher amount of energy will be needed to propagate a wavy crack over the same global distance as a straight crack. Also the changes in direction themselves will require additional energy.

Mode II interlaminar fracture toughness

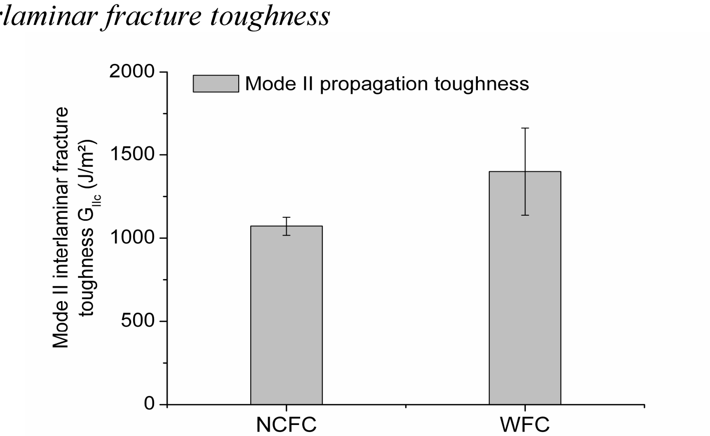


Fig. 3: Mode II interlaminar toughness test results for the NCFC and the WFC

As it was explained in paragraph 2.2, only propagation values for the mode II interlaminar fracture toughness (mode II critical energy release rate, G_{IIc}) were obtained. They are shown in figure 3. As for the mode I toughness, the mode II toughness of the WFC is higher (about 30 %) than that of the NCFC. A similar reasoning as described above for the mode I behaviour can be followed to explain this difference.

The mode I and II fracture toughness are important when considering impact of a composite material. Generally, it is a combination of both mode I and II crack propagation modes which causes the formation and growth of a number of delaminations.

As both the mode I and the mode II fracture toughness are higher for the WFC than for the NCFC, it can be concluded that a delamination in the NCFC will grow faster than a similar one in the WFC. Therefore, it is to be expected that any damage caused by impact will be more severe in the NCFC than in the WFC.

3.2 Impact tests

Absorbed energy

Figure 4 shows the absorbed energy for both materials as a function of the impact energy. Two impact energies were used: 3.5 and 7 J. For both impact energies, the NCFC absorbed about 10% more of the impact energy than the WFC. From this, and taking into account the discussion above about the interlaminar fracture toughness, it can again be expected that for the same impact energy, there will be more delamination damage in the NCFC than in the WFC.

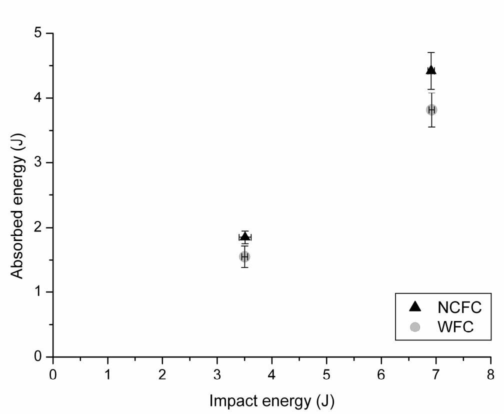


Fig. 4: Absorbed energy as a function of the impact energy for both materials.

Damage area

The projected damage area was determined as described in paragraph 2.2. The results can be seen in figure 5. As was predicted by the lower fracture toughness and the higher absorbed energy, the projected delamination area in the NCFC samples is consistently larger than in the WFC. Even taking into account the fact that there are 5 fabric layers in the WFC and only 4 in the NCFC, the difference is still significant. From the figure, it becomes apparent that there is a difference in damage area between the two fibre orientations used: for samples which have fibres oriented at ±45 degrees relative to the sample's length axis, the damage area is significantly larger than for samples with a 0/90 degree orientation. However, this is an artefact of the set-up used: during the drop weight impact tests, samples are fixed in a clamp with a square opening. This means that the span length of the fibres in the material will differ for the two orientations (see figure 6). Due to the larger span length in the samples with ±45 degree orientation, they will deflect a little more during impact. Therefore, more stresses are induced between the different layers and thus the damage area will be larger. This difference between the two fibre orientations becomes more apparent for higher impact energies.

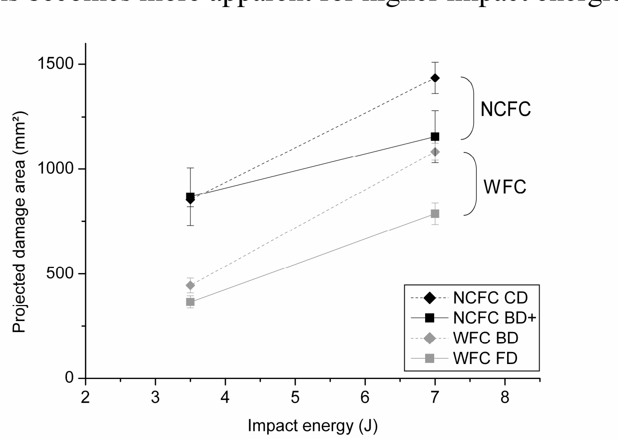


Fig. 5: The projected damage area, as measured with C-scan, as a function of the impact energy, for the different types of samples

(a) (b

Fig. 6: Illustration of the impact test set-up span length difference between ±45° oriented samples(a) and 0°/90° oriented samples (b)

3.3 Post-impact tests

Post-impact static tensile tests

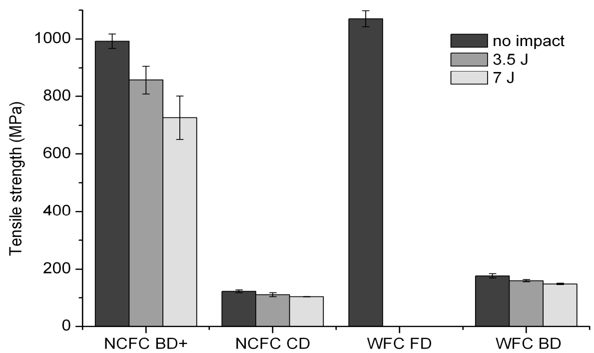


Fig. 7: Intact and post-impact tensile strength results for the different types of samples

The graph in figure 7 shows the tensile strength for the intact materials, together with the values obtained after an impact of 3.5 or 7 J. Only the strength of non-impacted samples is shown for the WFC FD samples, as the post-impact tests are still ongoing at this moment.

A clear influence of the impact damage on the strength can be seen for all tested sample types, but the difference is the most pronounced for the NCFC BD+. For these samples, an impact of 3.5 J causes a reduction in strength of about 12 %. After an impact of 7 J, this reduction has increased to about 25%. Due to the lower impact damage and the higher interlaminar toughness, we can expect that the tests on the WFC FD samples, will reveal that the influence of an impact on the static strength will be less severe than for the NCFC BD+ samples.

In the NCFC CD and WFC BD, which have fibre orientations ±45° with respect to the loading direction, there is no real difference in behaviour between the two materials: an impact of 3.5 J causes a strength reduction of about 9 %, which increases to about 15 % after an impact of 7 J.

Post-impact tensile-tensile fatigue tests

From the fatigue life curves for the different directions of the two materials, the maximum fatigue stress level corresponding to an average fatigue life of 10^6 could be found. This level was used for the post-impact fatigue tests. The stresses for the different directions of the two materials are listed in table 2. For NCFC BD+ samples impacted with an energy of 7 J, another series of tests was done at a slightly lower stress level (600MPa), to investigate the behaviour of the material more thoroughly.

In figure 8, the average fatigue life curve of samples with a ±45° fibre orientation (WFC BD and NCFC CD) is shown, together with the results of the tests after 3.5 J and 7 J impact loads. Also, the average post-impact quasi-static strength is indicated on the graphs. It can be seen that for both impact energies, the fatigue life of WFC BD samples is significantly lower (by about one order of magnitude) than for undamaged samples. However, due to the large standard deviation on the results, it is not clear whether a higher impact energy results in a shorter fatigue life. This, however, is clearly the case for the NCFC CD samples. An impact of 3.5 J decreases the fatigue life only marginally, whereas an impact of 7 J causes a reduction in fatigue life by an order of magnitude.

Table 2: Maximum fatigue stresses used for the post-impact fatigue tests

Type	σ_{max} (MPa)
WFC BD	115
NCFC CD	65
WFC FD	680
NCFC BD+	700

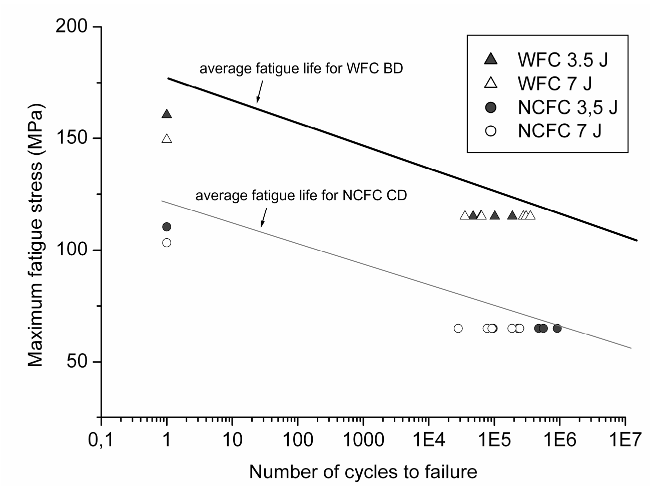


Fig. 8: Average fatigue life curve and post-impact fatigue test results for the ±45° oriented samples

Figure 9 shows the average fatigue life curve for the fibre dominated NCFC BD+ direction and the results of the post-impact fatigue tests. As said above, an additional series of fatigue tests was done up to 600 MPa for samples impacted with 7 J energy. Again it is clear that even a low energy impact of 3.5 J has a detrimental effect on the fatigue life of the material. Even though the variation in the results for the 7J impacted samples is rather large, the results indicate clearly that an impact of 7 J may lead to a severe decrease in fatigue life.

If these results are combined with those of the post-impact quasi-static tests (which are also shown on the graph in figure 9), it becomes apparent that the influence of an impact is less for lower post-impact fatigue loads than for higher loads. This means that impact does not merely cause a shift of the fatigue life curve, which is linear on a logarithmic scale. The post impact fatigue life curve will thus no longer be a straight line.

The post-impact tests on the WFC FD samples are still ongoing at the present time, so only the fatigue life curve of the non-impacted material is reported here (see figure 10).

Again, taking into account the better impact performance and interlaminar fracture toughness of the WFC material, it can be expected that the influence of the impact damage on the WFC FD samples will be slightly lower than for the NCFC.

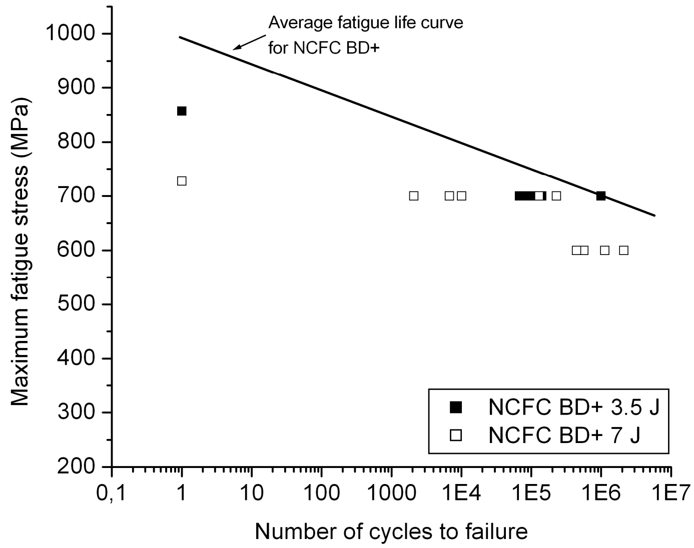


Fig. 9: Average fatigue life curve and post-impact fatigue test results for the NCFC BD+ samples

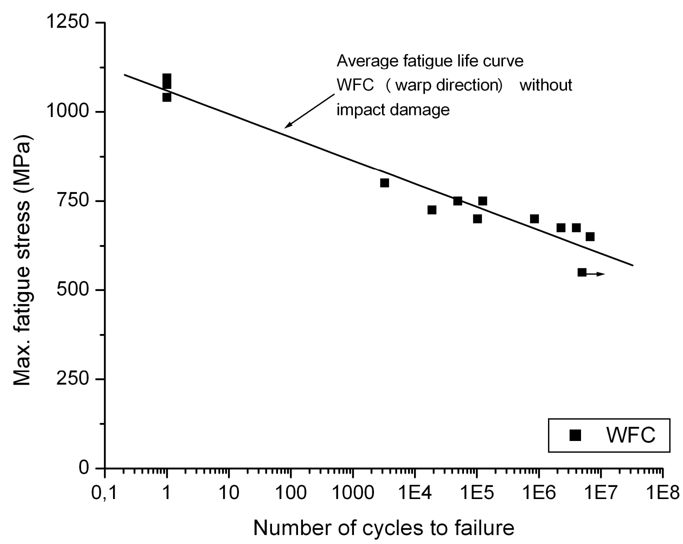


Fig 10: the average fatigue life curve for the WFC FD samples

4. CONCLUSION

In this study, the interlaminar fracture toughness mode I and II of a NCFC and a WFC was determined and linked to the impact properties and the post-impact static and dynamic tensile behaviour.
The initiation value of the mode I interlaminar fracture toughness was the same for both materials, which was explained by the use of the same resin in both materials. The

propagation value, however, was for both mode I and mode II tests lower for the NCFC than for the WFC, indicating a lower resistance to delamination growth along the fibre direction of the former. The impact tests confirmed this result: the NCFC absorbed a higher percentage of the impact energy, and the projected damage area caused by a same energy impact was consistently larger than for the WFC.

The low resistance to delamination growth of the NCFC was also noted in the post-impact tensile tests. A clear influence of the impact damage on the residual static strength was found.

The post-impact fatigue tests showed that a relatively low energy impact can cause a dramatic decrease of the fatigue life. An additional series of tests on the NCFC in fibre direction confirmed the hypothesis that the influence of the impact damage on this material is more severe for higher loading cases.

5. REFERENCES

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