Damage in Hybrid Composite Laminates†

HALEH ALLAMEH HAERY* and HO SUNG KIM

Mechanical Engineering, School of Engineering, Faculty of Engineering and Built Environment, The University of Newcastle, Callaghan, NSW 2308, Australia

KEYWORDS
Fatigue
Damage
Composite
Laminate
Fibre
Hybrid
Systems approach
Complexity
Mechanisms
Relative damage sensitivity factor

ABSTRACT
Hybrid laminates consisting of woven glass fabric/epoxy composite plies and woven carbon fabric/epoxy composite plies are studied for fatigue damage and residual strength. A theoretical framework based on the systems approach is proposed as a guide to deal with the complexity involving uncertainties and a large number of variables in the hybrid composite system. A relative damage sensitivity factor was developed for quantitative comparisons between non-hybrid and hybrid composites, which may be useful for developing inexpensive composites with low damage sensitivity. Hypotheses derived from the theoretical framework were tested and verified using evidence from both micro- and macro-scopic damage patterns. The first hypothesis was that the difference between two different sets of properties produces shear stress in interface between carbon fibre reinforced plastics (CRP) and glass fibre reinforced plastics (GRP), and eventually become a source for CRP/GRP interfacial delamination or longitudinal cracking. The second hypothesis was that inter-fibre bundle delamination occurs more severely to CRP sub-system than GRP sub-system.

1. INTRODUCTION

Composite is a structure consisting of two or more constituents having interfaces. It has been widely used as laminates in the aerospace industry and to a lesser extent in the automotive industry. Numerous research studies have been conducted to improve the behavior of composites under various loading conditions. They have shown that the composites made of one type of fibre reinforcement can be further improved by hybridizing for the optimum performance [1,2]. The hybrid laminates may be designed with two or more different types of fibre reinforcement. They are usually used when combination of properties of different types of fibres is required or when longitudinal as well as lateral mechanical performances are to be achieved [2,3]. Cost reduction of composite can also be achieved by incorporating laminates of low-cost but high performance fibres without much reduction of the mechanical properties of the original composite [4]. Hybrid laminates reinforced with glass and carbon fibres have indeed been found to be useful in practice, especially in automotive and aerospace industries [5–7]. The recent structural applications of hybrid composites have been even more extended by focusing efforts on energy reduction since the glass and carbon fibre reinforced polymer matrix proved to be significantly effective [9].

As the engineering structures are frequently subjected to fatigue loading, the fatigue analysis plays an important role in the design of structural components. The fatigue in composites has been recognized as a complex phenomenon compared to that of monolithic-materials. There have been numerous studies investigating the fatigue performance of glass/epoxy, carbon/epoxy, and their hybrid composites for the effect of cyclic loading on residual properties [10–20]. However, most of them have focused on non-hybrid composites such as unidirectional, multidirectional, and woven fabric, composites. Ozturk and Moore [16] investigated the tensile fatigue behavior of woven carbon/carbon laminates.
2. FATIGUE MICRO-DAMAGE MECHANISMS IN WOVEN FABRIC REINFORCED COMPOSITES IN THE LITERATURE

It is important to understand the damage mechanisms for improving fatigue performance of composites. Various fatigue micro-damage mechanisms for woven glass fabric reinforced composites have been suggested in the literature. The sequence of events, however, has not been agreed among researchers in the absence of solid evidence or generality of its nature for fatigue crack initiation point. Tanimoto and Amijima [10] studied woven glass fabric reinforced polyester composites with glass volume fractions of 29, 40 and 54% for micro-damage mechanisms without notch. They proposed three stages of damage process: (a) the first stage (up to 2% of its life span) was characterised such that the number of cracks initiate and form perpendicular to loading direction in resin-rich phase near transverse fibre bundles (weft) and remain in the matrix but no significant decrease in static strength; (b) at the second stage (2 to 50% of its life span), the cracks propagate through resin matrix surrounding the transverse fibres up to the adjacent longitudinal fibres and, as a result, residual strength continuously decreases with the cyclic loading; and (c) at the third stage (50 to 100%), the rate of decrease in static strength is reduced until the final failure. The sequence of the three stages is illustrated in Figure 1.

Fujii and Amijima [11] investigated fatigue micro-damage behavior of the similar laminates with a glass volume fraction of 33%. They also proposed three different stages of damage process but with difference sequence of events: (a) the first stage (up to 10% of its life span) was delineated with the crack initiation within the weft bundle (cracking of which is perpendicular to loading direction)—crack density after this stage did not increase significantly; (b) in the second stage (10 to 98% of its life span), debonds between weft and warp were formed leading to meta-delaminations at cross-over points before the final failure (as the third stage). Pandita et al. [18] also investigated the similar composite with epoxy matrix for a glass volume fraction of 50% for the same topic. They proposed essentially the same sequence as those by Fujii and Amijima [11]. Further, Gao et al. [27] reported more meaningfully with evidence on carbon woven fabric reinforced polyimide with a fibre volume fraction of 60%. They observed that the crack initiation frequently took place in the weft bundle. Their finding appears to be in agreement with Fujii and Amijima [11] for the initiation. Nonetheless, there always seems to be uncertainty to some degree regarding the nature of micro-damage mechanism and crack initiation position.

3. A THEORETICAL FRAMEWORK FOR FATIGUE DAMAGE PROCESS

Understanding of the fatigue damage process is important for developing new composites. The sequence for fatigue damage mechanisms coupled with a relevant description

Figure 1. Schematic representation of the tensile fatigue damage development in laminated glass composite laminate: (a) first stage (cracks remain in the resin phase); (b) second stage (transverse crack in the bundle yarn); (c) final failure.
leading to the final failure is the core of the process for a series of events. Various experimental techniques including in-situ and/or post-damage observation using microscopes [22], x-ray radiography [13], image processing algorithm [15], acoustic emissions [18] or c-scan [12] may be useful in conjunction with the post-damage analysis for collecting direct information. However, it is difficult to observe internally hidden in-situ damage mechanisms and its behaviour at a particular point does not necessarily represent all other points because of the inherent uncertainties originated from various sources such as in-homogeneity in both constituent materials and composite micro-structure due to the imperfect composite fabrication technology. For this reason, the post-damage analysis may be also useful for inferences of the damage mechanisms. More importantly, the facts based on the observations are about particular composite systems at a particular moment and therefore not necessarily applicable to other parts of composite system or other composite systems. For wider applications and better understanding, the post-damage analysis requires a theoretical framework for various interpretations and for navigating of collected/processed information towards the applications for improving design, performance, and optimized uses, of the composites in general. Most studies in the literature have focused on a limited number of parameters applicable to particular composites for fatigue damage load alone hybrid composites. Therefore, the following theoretical framework is proposed here for extending usefulness of limited data and observational facts.

3.1. Complexity and Systems Approach

The fatigue process of a monolithic-material as a constituent of a composite consists of commonly two stages—namely crack initiation and propagation prior to the final failure. The crack initiation is affected by a set of properties and is susceptible to the inherent defects in the material while the crack propagation is affected by another set of properties. Further, when different constituent materials are combined for a composite system, the fatigue behaviour of a constituent material is affected by other constituent material properties such as stiffness, strength, and relativity between properties of a composite system. The relativity is dependent on how much they are different from each other. The constituent materials as system elements within a composite system constrain each other during the damage process. Also the fatigue damage behaviour is affected by the interface conditions (e.g. bonding) between different materials [12]. They are further affected by large scale design factors such as geometrical variation (e.g. notch) and hybridization. The theoretical stress analysis and failure criteria [34,35] for the geometrical variation may be useful but their applications are limited to the cases of certain geometries prior to the fatigue damage.

When composites are hybridized for inter-plies of a laminate using woven fabric, three or more different constituent materials may be used, e.g. carbon fibre, glass fibre, and epoxy. For three different constituent materials, the locations of possible fatigue crack initiation points include: (a) matrix, (b) interface between fibre filaments within glass fibre bundle, (c) interface between fibre filaments within carbon fibre bundle (d) interface between matrix and glass fibre bundle, (e) interface between matrix and carbon fibre bundle, (f) glass fibre filament, (g) carbon fibre filament, (h) cross-over point for meta-delamination for carbon fabric, (i) cross-over point meta-delamination for glass fabric, (j) interface between glass-glass composite plies, (k) interface between carbon-carbon composite plies, and (l) interface between glass-carbon composite plies. Thus, twelve different locations are possible for a crack to initiate and propagate or to link with other crack grown from other locations. Accordingly, the number \( N \) of possibilities for different sequential patterns of damage events in terms of, at least, damage initiation locations are given by:

\[
N_f = n_f!
\]

where \( n_f \) is the number of possible locations of fatigue crack initiation. For example, \( N_f = 12! = 479,001,600 \) for the inter-ply hybrid laminates described above. If they are non-hybrid laminates e.g. glass reinforced plastic (GRP) laminates, the locations listed above, (a), (b), (d), (f), (h), and (j) may be applicable and the number of possible locations for initiation reduces to 720 (\( = 6! \)). Accordingly, a mechanism associated with a crack initiation within a transverse glass fibre bundle suggested by Pandita et al. [18] or Fujii and Amijima [11], or another similar mechanism associated with the initiation within resin-rich area outside glass fibre bundles (see Figure 1) suggested by Tanimoto and Amijima [10] in a deterministic manner may be one of 720 possible ones.

The way to reduce the complexity due to the uncertainty with a large number of possibilities for hybrid composites may be based on the systems approach. In general, there may be two different systems i.e. open and closed systems [25]. The open system consisting of input and output with system elements may be useful for understanding of the hybrid composite system damage. We may consider different size scale sub-systems within the open system, given that a large scale system behaviour in terms of damage (or cracking) is caused by small scale system behaviours. A small scale system behaviour is in turn caused by even smaller system behaviours. Thus, output from a small system constitutes input of a large system. Output from a large system is the manifestation of what has most likely taken place in the small scale system. Thus, as the system scale size becomes larger and larger, the uncertainty in damage behaviour decreases and accordingly stochastic process turns into more and more deterministic process. A hybrid composite is a relatively large system con-
sisting of sub-systems including interfaces. Each sub-system consists of constituent materials as system elements. Each constituent material may be regarded as the smallest system consisting of defects responsible for damage origin (or initiation). For example, a GRP laminate is one sub-system consisting of glass fibres, matrix and interfaces, and a carbon reinforced plastic (CRP) laminate is another sub-system consisting of carbon fibres, matrix and interfaces, for a hybrid system consisting of CRP laminates, GRP laminates (to be referred to as ‘CGRP hybrid system’) and interfaces. A certain type of loading (e.g. static loading, fatigue loading) or geometry variation (e.g. due to a notch) is an input to the system and damage is an output. One of the keys to understanding of hybrid system damage behaviour is to find differences between sub-systems provided sub-systems are well defined. The major differences may be found near or at interface zone between two different sub-composite systems. The reason is that the damage behaviour near or at interface zone is influenced by the difference between two sub-composite systems and hence is different from those of sub-composite systems.

In the systems approach, the identification of damage pattern(s), if any, according to crack initiation location at least and cracking direction for inferences of mechanisms in relation with expected behaviour may be useful. The main reason for this is that the damage pattern at a larger scale represents an output of the most probable damage mechanisms at a smaller scale. Therefore, the description of microscopic damage mechanisms without identification of the damage pattern at a larger scale may be not much useful.

The damage patterns generated by fatigue loading for brittle materials such as CRP may be expected to be similar to those by static loading. The reasons are that: (a) similar stress distributions are created by similar geometric variations; (b) the damage patterns are very closely associated with crack initiation sites and crack propagation; (c) the crack initiation sites and crack propagation are created by stress concentration caused by micro- and macroscopic-variation in geometry. Also, the strain at failure is expected to be similar as reported by Kim and Zhang [26]. The similarities in damage between static and fatigue loading are useful not only for reduction of complexity but also for theoretical formulation of residual properties [26].

The damage as system output created as a result of fatigue loading may be quantified in terms of stiffness or residual strength [26]. Two sets of constituent material properties for respective pre- and post- fatigue damages may be used as the characteristics of a composite system. The number of possible relative conditions for the initial constituent material properties of interest prior to damage \( N_{E,pr} \) can be worked out as:

\[
(N_{E,pr}) = n_e! \times N
\]

where \( N \) is a number of different properties, \( n_e \) is a number of different constituent materials. For example, if the hybrid system consisting of three different materials are used \( (N_{E,pr}) \) is found to be 18 \( (= 3! \times 3) \) for three different properties. An example of relative conditions applicable prior to fatigue damage is given by:

\[
E_E < E_G < E_C \quad (3)
\]

\[
\sigma_{EU} < \sigma_{GU} < \sigma_{CU} \quad (4)
\]

\[
\varepsilon_{CU} < \varepsilon_U < \varepsilon_{EU} \quad (5)
\]

where \( E_C \) = stiffness of carbon fibre, \( E_G \) = stiffness of glass fibre, \( E_E \) = stiffness of epoxy, \( \sigma_{EU} \) = ultimate stress of carbon fibre, \( \sigma_{GU} \) = ultimate stress of epoxy, \( \sigma_{CU} \) = ultimate stress of glass fibre, \( \sigma_{Cu} \) = ultimate strain of glass fibre, and \( \sigma_{Eu} \) = ultimate strain of carbon fibre, and \( \sigma_{EU} \) = ultimate strain of epoxy.

If we consider two sub-composite systems (i.e. CRP–sub system and GRP–sub system in the current work), a number of different constituent materials \( (n_c) \) in Equation (2) is replaced with a number of different sub-systems, for the number of possible relative conditions \( (N_{E,pr}) \). An example relative condition applicable prior to fatigue damage is

\[
E_{GRP} < E_{CRP} \quad (6)
\]

\[
\sigma_{GRPU} < \sigma_{CRPU} \quad (7)
\]

\[
\varepsilon_{CRPU} < \varepsilon_{GRPU} \quad (8)
\]

\[
v_{CRP} < v_{CRP} \quad (9)
\]

where \( E, \sigma, \varepsilon, \) and \( v \) denote stiffness, stress, strain and Poisson’s ratio, respectively, and capital subscripts indicate different sub-systems, and subscript \( u \) stands for ‘ultimate’. Consequently, the total number of possible damage patterns \( (N_T) \) characterized by crack initiation location, property numbers, and material/sub-system numbers leading to the residual properties is found to be

\[
N_T = N_f \times (N_{E,pr}) = n_f! \times N \times n_e!
\]

Accordingly, the total number of relative damage conditions for the hybrid system \( (N_T) \), in general, is calculated to be \( 8,945 \) \( = 479,001 \times 3 \times 3 \times 3 \times 3 \times 3 \times 3 \) when three constituent materials are considered, or it is \( 5,744 \) \( = 479,001 \times 2 \times 6 \times 6 \) when two sub-composite systems instead of materials are considered. Thus, the residual static properties, in general, are the ones obtained under one of the possible relative material property conditions. The possible number of combinations for residual property inequalities after fatigue \( (N_{E,po}) \) would be equal to those before fatigue \( (N_{E,pr}) \):

\[
(N_{E,po}) = (N_{E,pr}) = n_e! \times N
\]
Therefore, the total number of possible damage patterns \( (N_d) \) after fatigue in terms crack initiation site, number of properties, and number of material constituents/sub-systems is also equal to those prior to fatigue loading.

If a composite specimen has a geometrical variation (e.g. notch), the initial set of homogenous properties turn into in-homogeneous ones as an output as the damage progresses under fatigue loading. As a result of damage, the properties at the maximum stress point on a specimen are different from those at any other points. The damage, thus, can be in general characterized by in-homogeneity distribution of resultant material properties at an appropriate scale. A hybrid composite system prior to fatigue damage may be regarded as being homogenous including woven fabric at an appropriate scale, (knowing that a woven fabric is not homogeneous, for example, at a smaller scale because a set of properties at a cross-over point of woven fabric are different from those of other points) but, as the damage progresses, in-homogeneity is created and more and more widely distributed. Such conditions given by Equations (3) to (5) or (6) to (9), thus, will be rearranged depending on the location at a specimen. The initial strength following the fatigue damage is then altered for the resultant residual properties for a given geometry condition.

### 3.2. Relative Damage Sensitivity Factor for Comparing Two Different Composite Systems

Design of complex (or hybrid) composites for improvement can be an evolutionary process unless a creative process is adopted. In other words, existing composites may be modified and compared in a process of decision making. If the modification is made by replacing part of an existing composite with new one, comparisons should be made. Two different ways for making comparisons may be considered. One way is to compare damage results (e.g. residual strength) directly from two different composite systems for absolute damage. The other way is to find, and compare for, a relative change rate of damage in its own composite system for the common variation of geometry or/and loading conditions between two different composite systems. It would be, however, implicit and its benefit would not much be known without a quantitative description despite the fact that such comparisons may be useful for a low cost hybrid composite development. The following procedure is proposed for a relative damage sensitivity factor which will be useful in such a situation.

If we choose and consider two particular composite systems for comparing residual properties, we need to define the residual (structural) strength reduction rate or increase rate—for conventional composite system (e.g. GRP system) \( (R_o) \), and hybrid composite system (e.g. CGR hybrid system) as a large new system \( (R_n) \):

\[
R_o = \frac{S_{ag}}{S_{ag}^{oc}} \quad (12)
\]

and

\[
R_n = \frac{S_{ag}}{S_{ag}^{oc}} \quad (13)
\]

where \( S_{ag}^{oc} \) is an apparent residual strength for new geometry (e.g. due to a different notch size or creation of a hole) and original (or conventional) composite system, \( S_{ag} \) is an apparent residual strength for original geometry and original composite system, \( S_{ag}^{oc} \) is an apparent residual strength for new geometry and new composite system (or hybrid), and \( S_{ag}^{oc} \) is an apparent residual strength for original geometry and new composite system.

It is possible for the two different composite systems i.e. original (or conventional) composite system (CCS) and new hybrid system (NHS) to have the following cases as a result of damage:

- Case 1: \( R_o > 1, R_0 > 1, R_n > R_0 \)—both CCS and NHS strengthened,
- Case 2: \( R_o > 1, R_0 > 1, R_n < R_0 \)—both CCS and NHS strengthened,
- Case 3: \( R_o > 1, R_0 < 1 \)—CCS weakened but NHS strengthened,
- Case 4: \( R_o < 1, R_0 > 1 \)—CCS strengthened but NHS weakened,
- Case 5: \( R_o < 1, R_0 < 1, R_n < R_0 \)—both two composite systems weakened, and
- Case 6: \( R_o < 1, R_0 < 1, R_n > R_0 \)—both two composite systems weakened.

For relative damage sensitivity for two different composite systems (CCS and NHS), the following factor, \( q \), (this factor will be referred to as “relative damage sensitivity factor”) can be found to be applicable for all the possible Cases:

\[
q = \frac{R_0}{R_n} \quad (14)
\]

According to Equation (14), \( q \) is found as follows: \( q < 1 \) for Case 1; \( q > 1 \) for Case 2; \( q < 1 \) for Case 3; \( q > 1 \) for Case 4; \( q > 1 \) for Case 5; and \( q < 1 \) for Case 6. In general, \( q \) approaches one if no difference in properties of both composite systems is caused by any change in input (e.g. fatigue loading), or \( q < 1 \) if a NHS is less sensitive to damage than CCS.
or $q > 1$ if NHS is more sensitive to damage than CCS. For developing a new composite system, the smaller $q$ the better. Thus, Equation (14) is a generalized criterion indicating a relative damage sensitivity useful for comparing two different composite systems for the same variation of geometry or/and loading condition. Equations (12)–(14) may be applicable to static cases also in the absence of fatigue damage. If the residual strength ($S$) is replaced with the residual stiffness, the same principle is applicable for the residual stiffness comparison for two different systems.

4. EXPERIMENTAL DETAILS

The experimental details given here are adopted from the previous papers [21,31] for part of the current experimental work to provide self-sufficient information.

4.1. Structure of Woven Fabric

The structure of a woven fabric is characterized by the following parameters: inter-crimp length, bundle width at crimp region, crimping length, and bundle thickness. The inter-crimp length is the distance between two neighboring crimps while the crimping length is the one for the undulating region. The bundle width at the crimp is the one for the transverse bundle, and the bundle thickness is the average thickness of the longitudinal (or horizontal) bundles [27]. The characteristic measurements for the architecture of carbon and glass woven fabric are shown in Table 1.

4.2. Specimen Preparation

Plain weave C-glass fibre fabric or plain weave 3K-carbon fibre fabric were used for fabricating CGRP plies with a matrix of D.E.R. 331 epoxy resin which is uniformly mixed with a Jointmine hardener, type (905-3S), with a 2:1 ratio by weight. The laminates consisting of twelve plain weave plies were fabricated with the hand lay-up method for both glass reinforced composite (GRP) system as the control and CGRP hybrid system for specimen dimensions given in Figure 2.

The CGRP hybrid system manufactured consisted of six GRP plies in the middle between CRP plies at top and bottom symmetrically. The outer CRP plies are intended for a relatively high tensile strength and stiffness but low fracture strain while inner GRP plies are for a relatively low cost and thermal conductivity but for high impact strength [28]. The properties of woven fabric C-glass and woven fabric 3K-carbon plies used here were taken from the previous studies by Zahari et al. [29] and Allameh Haery [21] are given in Table 2. The measured volume fractions were 51% for glass fibre in GRP, 66% for carbon fibre in CRP, and the volume fraction of both fibres in hybrid CGRP is 59%.

A symmetrical stacking sequence, (0/90)$_{3s}$, was chosen for both GRP and CGRP hybrid systems by considering warp as 0° and weft as 90° directions. The specimens, 210 mm long, 40mm wide, and 3 mm thick, for fatigue tensile tests were cut from 250 × 350 mm plates using a CNC tooling machine. A circular hole with a diameter of 5 mm or 10 mm was drilled at the center of each specimen to give a notch effect. Figure 2.

4.3. Mechanical Testing and Damage Examination

The manufactured specimens were loaded for fatigue

---

**Table 1. Characteristic Measurements for Fibre Architecture of Carbon and Glass Woven Fabric.**

<table>
<thead>
<tr>
<th></th>
<th>Carbon Fibre</th>
<th>Glass Fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inter-crimp Length (mm)</strong></td>
<td>3.70</td>
<td>2.860</td>
</tr>
<tr>
<td>Average</td>
<td>1.338</td>
<td>2.084</td>
</tr>
<tr>
<td>CV (%)</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td><strong>Bundle Width at Crimp Region (mm)</strong></td>
<td>1.739</td>
<td>1.942</td>
</tr>
<tr>
<td>Average</td>
<td>2.787</td>
<td>3.073</td>
</tr>
<tr>
<td>CV (%)</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td><strong>Crimping Length (mm)</strong></td>
<td>2.425</td>
<td>2.452</td>
</tr>
<tr>
<td>Average</td>
<td>2.950</td>
<td>3.929</td>
</tr>
<tr>
<td>CV (%)</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td><strong>Bundle Thickness (mm)</strong></td>
<td>0.109</td>
<td>0.104</td>
</tr>
<tr>
<td>Average</td>
<td>1.79</td>
<td>3.56</td>
</tr>
<tr>
<td>CV (%)</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

1. CV is the coefficient of variation
2. $n$ is the number of specimens

---

*Figure 2. Specimens used for two different hole sizes of 5 mm and 10 mm.*
damage using an Instron 8802 servo-hydraulic testing machine. A constant crosshead speed of 1 mm/min was chosen for the static tensile test at room temperature. For tension-tension fatigue tests, two load ratios \((R = \text{minimum load}/\text{maximum load})\), 0.1 and 0.25, with a sinusoidal frequency of 10 Hz, were also chosen. The maximum load for the fatigue was fixed to be a 70% of ultimate tensile load for each composite system (i.e. control GRP and CGRP hybrid). Each fatigue testing was stopped at \(4 \times 10^4\) cycles for a subsequent static tensile test for measuring the residual strength. The number of cycles \((4 \times 10^4)\) was chosen considering that it is within a range of some beneficial effects which are expected due to the stress redistribution for similar composite systems in the literature [20]. At least five specimens were tested for each case.

For all the microscopic examinations, a position approximately 10 mm above or below a straight line crossing the minimum ligament section of the specimen was taken to view thickness area surface. Loading of each specimen shown in all the images is in the horizontal direction.

5. RESULTS AND DISCUSSION

5.1. Residual Strength Prior to Fatigue Damage

The ultimate tensile loads without fatigue damage for control GRP system and CGRP hybrid system obtained previously [21] are given in Table 3. It is seen that the apparent strength decreases as expected with increasing hole size from 5 mm to 10 mm in both GRP and CGRP hybrid systems. The reduction rate \((R_a)\) due to the hole size increase for GRP system [see Equation (12) for \(R_a = \frac{S_{\text{ult}}}{S_{\text{ult}}}\)] is found to be 24% while \(R_a\) [see Equation (13)] is found to be 10% for CGRP hybrid system. As a result, the relative damage sensitivity factor \((q)\) becomes 0.844 \([< 1]\)—see Equation (14)] indicating that damage in CGRP hybrid system is less sensitive than GRP system to the hole size increase.

![Table 3. Average Ultimate Tensile Loads Obtained from Static Tensile Tests (without fatigue damage). The Reduction Rates Due to Hole Size Change from 5 to 10 mm are Given in Parenthesis.](image)

<table>
<thead>
<tr>
<th>Hole Size (mm)</th>
<th>GRP System</th>
<th>CGRP Hybrid System</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mm hole</td>
<td>11.86 (R_a = 76%)</td>
<td>21.48 (R_a = 90%)</td>
</tr>
<tr>
<td>10 mm hole</td>
<td>8.98</td>
<td>19.32</td>
</tr>
</tbody>
</table>

5.2. Residual Strength After Fatigue Damage

A summary of ultimate tensile loads obtained at two different load ratios for two different hole sizes and two different composite systems is given in Table 4. Each value in parenthesis is a reduction rate \((R_a \text{ or } R_b)\) due to fatigue damage with reference to the corresponding static ultimate load. The load ratios and hole sizes were intended to provide a wide range of different damage conditions.

5.3. Hypotheses and Damage Examination for CGRP Hybrid Systems

Some complexity in deformation leading to damage may be caused by the woven fabric cross-over points. The expected deformation, though, causing damage due to differences between constituent materials may be useful for setting up a hypothesis. An illustration for the deformation is introduced in Figure 3. It may be similar to those of a non-hybrid laminate given by Desai and McGarry [30], and Shuler et al. [22] but is for more specific deformation and is different in relation with the hybrid composite system. The longitudinal tensile loading straightens the longitudinal fibre bundles and simultaneously the following events take place at around the cross-over point [Figure 3(a)]: (i) bending of transverse fibre bundles and increasing of contact pressure; (ii) bending of longitudinal fibre bundle (which is straightening); and (iii) increasing of distance between transverse and longitudinal fibre bundles along the longitudinal fibre bundle but decreasing along the transverse fibre bundle (due to the contact pressure and bending of transverse fibre bundle). The last event would create a source for delamination between longitudinal and transverse fibre bundles. The bending in the other events is accompanied by not only normal stress but also shear stress. The maximum bending of either longitudinal or transverse fibre bundle takes place at the cross over point. The shear stress is, therefore, likely responsible for the longitudinal cracking within a transverse fibre bundle or a longitudinal fibre bundle if happens. Otherwise, transverse cracking in transverse fibre bundle is expected due to either the principle stress in the longitudinal loading direction or a
splitting force when width is much larger than thickness of transverse fibre bundle (weft).

When GRP sub-system is interfaced with CRP sub-system for hybridization as illustrated in Figure 3(b), the following may be considered: the carbon fibre bundles are stronger and stiffer [see Inequalities (3) and (4)] but lower in Poisson’s ratio than glass fibre bundles. The localized (bending and shear) deformation of longitudinal glass fibre bundles of GRP system near CRP ply is, thus, relatively compliant to the straightening of longitudinal carbon fibre bundles. The carbon fibre bundles of CRP system has hence more straightened than glass fibre bundles because their high stiffness as illustrated in Figure 3(b). Therefore, the bending with shear deformation (causing a longitudinal cracking) of the transverse carbon fibre bundles would take place more near the interface than those far away and surrounded by CRP plies. More importantly, such compliant behaviour of longitudinal glass fibre bundles with respect to the longitudinal carbon fibre bundle produces a difference in transverse elongation between two dissimilar plies despite the external iso-strain loading. Also, more obviously the difference in Poisson’s ratio between two different sub-composite systems (see Table 2) produces different internal force directions as illustrated in Figure 3(c)—a larger lateral contraction of glass fibre bundles and a relatively smaller lateral contraction of carbon fibre bundles. Accordingly, it can be hypothesized (to be referred to as the First Hypothesis) that the difference between two different sets of properties produces shear stress

\[ \text{Table 4. Average Ultimate Tensile Loads Obtained from Static Tensile Tests After Being Fatigue Damaged. The Strength Reduction Rates Due to Fatigue Damage are Given in Parenthesis.} \]

<table>
<thead>
<tr>
<th></th>
<th>GRP System</th>
<th></th>
<th>CGRP Hybrid System</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 mm hole</td>
<td>10 mm hole</td>
<td>5 mm hole</td>
<td>10 mm hole</td>
</tr>
<tr>
<td>Ultimate Tensile load (kN) ( (R = 0.1) )</td>
<td>10.18 ( (R_b = 85.9%) )</td>
<td>7.55 ( (R_b = 84.1%) )</td>
<td>18.53 ( (R_b = 86.3%) )</td>
<td>15.14 ( (R_b = 88.3%) )</td>
</tr>
<tr>
<td></td>
<td>( q = 0.995 )</td>
<td>( q = 1.074 )</td>
<td>( q = 0.995 )</td>
<td>( q = 1.052 )</td>
</tr>
<tr>
<td>Ultimate Tensile load (kN) ( (R = 0.25) )</td>
<td>9.12 ( (R_b = 77.0%) )</td>
<td>6.54 ( (R_b = 72.9%) )</td>
<td>15.80 ( (R_b = 73.5%) )</td>
<td>13.40 ( (R_b = 69.3%) )</td>
</tr>
</tbody>
</table>

\[ \text{Figure 3. Schematic representation: (a) loading direction with cross-over point; (b) longitudinal and transverse fibre bundles near CRP/GRP interface before and after longitudinal tensile loading; and (c) shear force directions in CRP/GRP interface due to difference in Poisson's ratio. Note that the contact points between transverse fibre bundles in '(b)' and '(c)' are in reality at random.} \]
in CRP/GRP interface, and eventually become a source for CRP/GRP interfacial delamination or longitudinal cracking. Further, two sub-systems can be compared at a large scale for general macroscopic fatigue damage with the benefit of discussion here and the initial material conditions given in Inequalities (3)–(5). Then, the likelihood that the three events, ‘(i)’, ‘(ii)’ and ‘(iii)’, described above take place more intensively in CRP sub-system than in GRP sub-system allowing us to hypothesize (to be referred to as the Second Hypothesis) that inter-fibre bundle delamination occurs more severely to CRP sub-system than GRP sub-system.

Fatigue micro-cracking near CRP/GRP interface observed are shown for some typical ones in Figure 4. The dashed lines and dotted lines were superimposed on images along cracks indicate crack locations for longitudinal and transverse cracks, respectively. Figure 4 shows a crack formed for an interfacial delamination and then branched out at the multiple points to turn into transverse cracking in the transverse carbon fibre bundle. Also, a long longitudinal crack in a longitudinal carbon fibre bundle cross-jointed with one of the transverse cracks originated from the CRP/GRP interfacial delamination is seen. The crack branching tends to be in the transverse direction, indicating that it is affected by the longitudinal principle stress eventually. The crack opening magnitudes indicate that the crack branching is evidently emanated from the interfacial delamination. Therefore, the evidence here supports the First Hypothesis set up above.

However, the observations are not sufficient conditions but necessary for the possibility that the interface is the most probable damage initiation site constituting a macroscopic damage pattern.

At a larger scale, it is commonly observed that the inter-fibre bundle delamination occurs more in CRP sub-system than GRP sub-system as shown in Figure 5. The macroscopic damage pattern along with the micro-cracking (Figure 4) appears to be sufficient to support both the First and Second Hypotheses. Figure 6 shows the macroscopic damage pattern under static loading. It appears similar to that under fatigue loading (Figure 5) to support the similarities between static and fatigue loading discussed under the theoretical framework.

5.4. Other Patterns of Micro-damage

Other patterns of micro-damage in terms of crack initiation location and cracking direction were observed and summarised in Figure 7. As expected and discussed under Section 3, many different patterns were found even though some of those were not eventuated for observable macroscopic damage patterns. They include: transverse cracking initiated from delamination [Figure 7(a), (b)]; inter-ply delamination [Figure 7(c)]; longitudinal crack in transverse carbon fibre bundle [Figure 7(d)]; cavity in transverse carbon fibre bundle [Figure 7(e)]; GRP/GRP interface delamination and transverse cracking [Figure 7(f)]; cavity in transverse glass fibre bundle and longitudinal cracking [Figure 7(g)]; transverse cracking between two cavities in transverse glass fibre bundles [Figure 7(h)]; transverse cracking through both transverse and longitudinal fibre bundles [Figure 7(i)]; transverse cracking originated from interface [Figure 7(j)]; and longitudinal cracking in transverse glass fibre bundle [Figure 7(k)]. The damage initiation locations discussed un-

![Figure 4](image-url) Damage near CRP/GRP interface with transverse cracking in a longitudinal carbon fibre bundle, and longitudinal cracking near GRP/GRP interface causing cross-over point delamination near GRP/GRP interface. The dashed and dotted lines indicate longitudinal and transverse cracking, respectively [31].

![Figure 5](image-url) Inter-fibre bundle delamination at a large scale on thickness area of test specimen with a hole diameter of 5mm after the fatigue damage at R = 0.1. (The inter-fibre bundle delamination appears as the darkest colour and gaps in contrast with undamaged CRP plies) [31].

![Figure 6](image-url) Inter-fibre bundle delamination at a large scale on thickness area of test specimen with a hole diameter of 10 mm.
der Section 3 appears to be in line with these observations although some smaller scale ones were not confirmed (e.g. initiation within fibre filament).

6. CONCLUSIONS

- A theoretical framework is proposed as a guide to deal with the complexity involving uncertainties and a large number of variables in the hybrid composite systems.
- A relative damage sensitivity factor has been developed for the quantitative comparison between non-hybrid and hybrid composite systems.
- New damage mechanisms of hybrid laminates due to the dissimilarity between GRP and CRP systems were hypothesized and tested to be valid with the evidence based on macroscopic and microscopic examinations.
- The most probable initiation site of micro-fatigue damage mechanisms has been deduced.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support for UNIPRS and UNRS from the University of Newcastle.

REFERENCES
