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A Review of Void Formation and its Effects on the Mechanical Performance of Carbon Fiber Reinforced Plastic

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Carbon fiber reinforced plastic (CFRP) is ideal for high performance of mechanical properties. However, during the manufacturing process of CFRP, defects or flaws can easily be introduced into the material, among which void is the most common one. Many factors contribute to the formation of void including the curing pressure, resin system, environmental conditions and so on, some of which are almost unavoidable. The presence of voids results in a reduction of the mechanical properties of CFRP, which has been the subject of many researchers for several decades. The aim of this paper is to summarize state-of-the-art studies on void formation and its effects on the mechanical properties of CFRP.

Key words: composites, CFRP, void, mechanical properties.

1. Introduction

Carbon fiber reinforced plastic (CFRP) is light weight and has high specific stiffness and strength, all of which make it suitable for a wide range of high responsibility applications from spacecraft to sports equipments to satellite dishes. However, there are still some challenges for CFRP to achieve the desired high performance of mechanical properties such as high strength and long service life. To this end, many techniques have been developed to fabricate such a material to meet the requirements of different applications, which aim to combine the carbon fiber and resin into a well-consolidated material. Considering the status of fiber and resin before consolidation, there are two ways to fabricate CFRP. One way is for the fiber and resin to be separate before manufacturing and another is a combination of fiber and resin in pre-preg form. Consequently, there are two manufacturing techniques: the out-of-autoclave process and the autoclave process. Although the selection of manufacturing technique depends mainly on the size and quality of CFRP product, the out-of-autoclave process, such as liquid composite molding (LCM), is predominant due to its less expensive equipment, while the autoclave process is almost the only means to fabricate CFRP structures for aerospace applications, especially for the primary and secondary structures.

The manufacturing of CFRP is complex due to the fact that many control parameters are involved, and expensive in terms of capital investment and time. Defects such as void, contamination or delamination have many opportunities to be introduced into the material and their appearance reduces the mechanical performance of CFRP as a result. Among more than 130 defect types that can be identified during the manufacturing of CFRP [1–5], void is the most important manufacturing defect due to the fact that many of the other defects occur more rarely compared to void formation. Therefore, as many scientific studies reveal, it is critical to establish the acceptable level of voids in designing CFRP structures because of their detrimental effects on the mechanical performance of CFRP products, as many scientific studies revealed. An excessively strict acceptance criterion may unnecessarily reject many CFRP products that could perform satisfactorily, which as a result increases the manufacturing costs. On the contrary, if the damage of voids is underestimated, some CFRP products may fail in service. In practice, both situations can be avoided by choosing a reasonable acceptance criterion, which should be based on a good understanding of the effects of voids on the mechanical performance of CFRP products [6]. The purpose of this paper is to review state-of-the-art studies on the analysis of void formation and the effects of voids on the mechanical properties of CFRP. The paper is organized as follows: after the introduction given in this section, factors contributing to void generation are summarized in Sec. 2 and its effects on mechanical properties of CFRP are shown in Sec. 3, which is followed by the discussion and conclusions drawn in Sec. 4.

2. Void formation

Voids are one of the most common manufacturing induced defects; they indicate the presence of air in the matrix [7]. Due to the difference of CFRP manufacturing techniques between the autoclave process and the out-of-autoclave process, factors contributing to void formation are accordingly different, which is discussed in details below. Note that due to the limitation of the literature, LCM is only highlighted in the present work as the representation of the out-of-autoclave process.

2.1. Out-of-autoclave process

In the LCM process, a fibrous preform is first placed in a mold. The mold is then sealed and liquid resin is injected to saturate the preform and cover all the fibers. After the thermoset resin is cured, CFRP products are finally obtained.

CFRP fabricated through LCM exhibit defects during the resin infiltration process, which leads to flaws such as void in the cured material. Void content is influenced by the initial bubbles in the matrix resin, void formation during the impregnation and void growth or shrinkage during the cure. Although voids can originate from different sources, mechanical air entrapment is believed to be the primary cause of void formation in LCM [8, 9]. Moreover, reported works reveal that the preform geometry, mold complexity, resin properties, vacuum pressure and flow rate potentially influence the relative size and location of voids.

2.1.1. Temperature. The mold temperature, resin injection temperature and resin curing temperature are the temperatures used during the manufacture of CFRP [10–14].

Mold temperature contributes to determine the viscosity of the resin and thus drives the flow velocity of the resin in the preform. This velocity is essential in the mechanism causing the formation of voids in the filling of preforms. Studies have shown that increasing the mold temperature and the curing temperature caused an increase in the glass transition temperature of the infused laminate [10]. When the laminate was infused with a high mold temperature, the gap between this infused temperature and the curing temperature was reduced, which increased the degree of polymerisation of the material. In addition, higher process temperatures cause an expansion of voids within the material, which was proved by Njionhou *et al.* in [14].

2.1.2. Pressure. Inlet pressure in resin transfer molding (RTM) or vacuum pressure in vacuum-assisted resin transfer molding (VARTM) affects not only the void content but also the fiber volume fraction.

The effect of injection pressure on void content was studied in [15]. Two behaviors of void formation under different injection conditions were reported, as shown in Fig. 14, page 1866 in [15]. For the low injection pressure, the percentage of voids increased along the injection length (from the inlet to the outlet), while for higher injection pressures, the percentage of voids decreased. So it could be concluded that macro-voids were formed at low injection pressures and micro-voids at high injection pressures.

Meanwhile, it was found that stronger vacuum and higher mold temperature could better control and increase the fiber volume fraction but required a reduced inlet pressure for minimizing the void content [13]. Increasing the pressure at the vent, while the resin finished saturating the stack, successfully reduced the void content [16]. As a result, an optimal manufacturing method was assessed. At the beginning of infusion, high vacuum pressure was able to reduce the chance of void formation due to entrapped air. After the resin arrived at the vent, high pressure restrained resin evaporation. In this way, the two primary causes of void formation were minimized and low void content CFRP was obtained.

2.1.3. Resin properties. The evaporation of resin is another source of void formation in LCM. In [16], it was found that resin evaporation was unavoidable and could reach a constant speed after a certain period. As shown in Fig. 1, L is used to represent the amount of air evaporated from resin over every two minutes. It can be seen that at the beginning the evaporation speed was very high, but it decreased quickly. The constant evaporation speed beginning at 20 mm and after 30 min showed that evaporation, which has the potential to generate voids, cannot be avoided and any attempts to restrain resin evaporation, for example, by degassing the resin, are pointless.

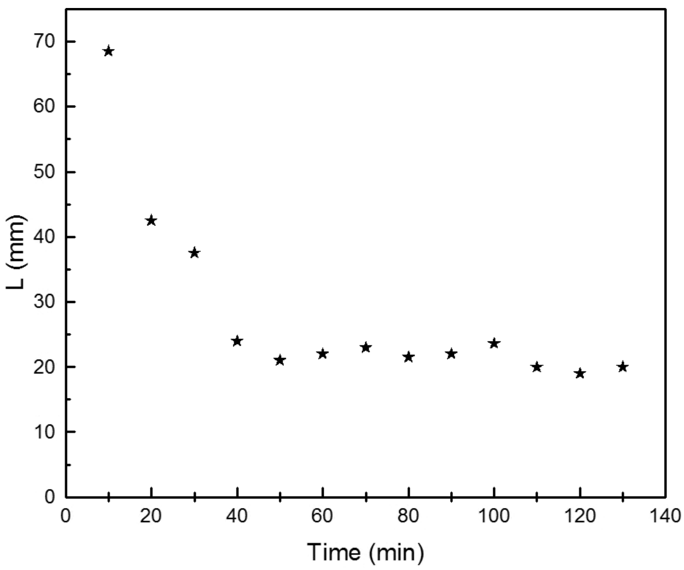


FIG. 1. The results of resin evaporation (reprinted with permission from [16]).

In [17], it was assumed that the resin system had no effect on macro-void formation, which was based on the experimental results obtained in the same study. The trends of macro-void formation with the vinylester and epoxy anhydride resins were similar, as shown in Fig. 14, page 108 in [17]. It was assumed that void formation was determined by the architecture of the fibrous reinforcement rather than the resin.

2.1.4. Resin flow. The resin flow is primarily influenced by the fiber preform geometry, mold complexity and resin properties. In addition, the processing parameters imposed on the system, for example, the vacuum pressure in VARTM and the injection flow rate in RTM, have a significant effect on the resin flow and consequently influence the relative size and location of the entrapped air voids in the resulting composite material.

It was concluded that void formation in RTM highly depended on resin velocity and the surface tension at the flow front during mold filling [18, 19]. Since the capillary number was regarded as the decisive factor affecting void formation in RTM, the mathematical model – a function of capillary number, could be used to predict the size and content of air voids [19]. A detailed study on void formation caused by resin flow can be found in [20].

An optimization based on the analysis of the capillary number at the fluid flow front position was carried out in [21]. The optimization showed a minimization of not only macro-voids but also micro-voids for the similar filling times. Therefore, optimization of resin flow is a good method to increase the performance of CFRP by minimizing the percentage of voids.

A resin flow model concerning the post-filling stage was proposed in [22]. It was found that certain resistance attached at the vent benefited the resin by saturating all the fiber tows, postponed the resin to bleed out through the vent and consequently reduced the chances for void formation.

The effect of resin flow paths on the formation and size of voids was investigated in [23]. It was found that when the resin flow direction did not coincide with the principal direction of the fabric, the meso-voids increased with an increase of the angle between the resin flow direction and the principal direction of the fabric, as shown in Fig. 19, page 17 in [23].

2.1.5. Fiber content. Fiber content was found to be an important factor to affect not only the number of voids but also the contribution of irregularly-shaped voids [24]. It was found that the number of voids decreased moderately with increasing fiber content from 13.5 to 27.5%, as shown in Fig. 4, page 5 in [24]. Void areal density decreased from 10.5 to 9.5 voids/mm^2 as fiber content increased. In addition, the contribution of irregularly-shaped voids was lowered from 40% of total voids to 22.4%.

2.2. Autoclave process

In the autoclave process, voids are formed mainly due to the entrapment of air in resin rich areas during the formulation of pre-preg materials, the moisture absorbed during the storing, volatile resin components during the processing, inadequate values of temperature and pressure during the curing, tearing in the vacuum bag during a cure cycle and so on [25, 26]. So far, many studies have been performed to restrain the void formation. Some of these studies found proper cure parameters such as pressure, duration or temperature to reduce the appearance of voids.

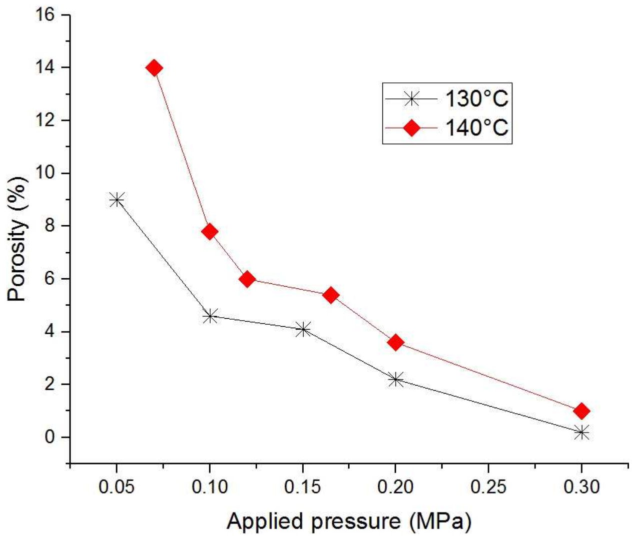
2.2.1. Curing pressure. It is well known that void formation is very sensitive to curing pressure, based on which specimens with different void content are manufactured for scientific purposes. As early as in 1995, Olivier *et al.* applied different curing cycle pressures to obtain carbon/epoxy unidirectional laminates with the void content in the range from 0.3 to 10% [27]. Liu *et al.* examined the effects of various consolidation pressures on void content in [28]. Different cure pressures: 0.0, 0.1, 0.2, 0.4 and 0.6 MPa, were selected to produce laminates with different void content ranging from 0 to 4%. An exponential decrease relationship between void content and cure pressure was obtained, as shown in Fig. 3, page 89 in [28]. The curing cycle can be optimized by altering the moment of applying pressure within the range of minimum viscosity. It was proved in [29] that the cure cycle could be shortened by nearly one hour if an appropriate pressure was applied [29]. Gu *et al.* also found that the porosity of unidirectional laminate decreased nearly exponentially with an increase of pressure applied to two different pre-pregs [30]. Zhu *et al.* found that the voids were spherical and small at higher pressure and became larger and elongated as the pressure went down [31].

All the mentioned studies agree that high curing cycle pressure helps to reduce void formation. In addition, the shape and size of void are affected by curing pressure too, as shown in Fig. 3, page 89 in [28].

2.2.2. Curing temperature. The effect of curing temperature on void formation is not clear yet. Gu *et al.* found that voids tended to grow at a higher curing temperature, as shown in Fig. 2. They suggested that to minimize the void defect, low temperature should be used during composite processing [30]. On contrary, curing temperature was found to have almost no influence on void formation in [32]. This difference may be caused by using different resin system or by different experimental conditions.

Although curing temperature hardly affects void formation, it influences the mechanical performance of CFRP. High curing temperature introduces important internal stresses into CFRP while low curing temperature causes the decrease of mechanical properties of CFRP due to a lower degree of polymerization achieved after cure [11, 12]. Therefore, thermal optimization is necessary to increase the mechanical performance of CFRP parts as well as to reduce the processing time.

a)



b)

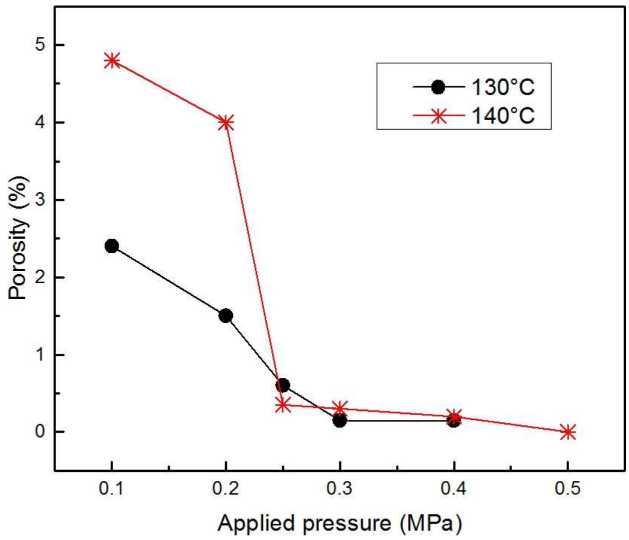


FIG. 2. Effect of curing temperature on void formation (reprinted with permission from [30]): a) epoxy BA9916 pre-preg, b) epoxy QY8911 pre-preg.

2.2.3. Resin system. The volatile resin components also affect void formation. GU *et al.* tested the influence of resin variety on void formation under the same processing conditions [30]. The gel temperature was 130°C and the relative humidity was 90%. The experimental results showed that epoxy BA9916 had a higher probability of void initiation and growth than bismaleimide QY8911. More numerous and larger voids were generated in BA9916 as shown in Fig. 3

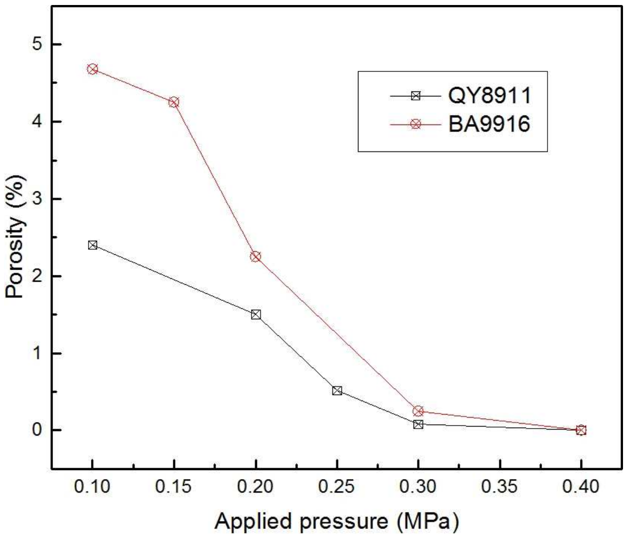


Fig. 3. Effect of resin system on void formation (reprinted with permission from [30]).

2.2.4. Stacking sequence. Stacking sequence may affect the distribution of resinrich areas in CFRP products and, as a result, a void formation. Zhu *et al.* found that different stacking sequences caused not only different void content but also different shapes, sizes and distributions of voids [33]. Two stacking sequences: $[(\pm45)/(0,\ 90)/(\pm45)_2]_s$ (sp1) and $[(\pm45)/0_4/(0,\ 90)/0_2]_s$ (sp2) were adopted to fabricate specimens by using the same pre-preg materials and curing pressure. The analysis results showed that two types of specimens were of highly different void content, which indicated the influence of stacking sequence on void formation as shown in Table 1, page s471 in [33]. In their further study different stacking sequences resulting in different tensile strengths caused mainly by different void content were reported [31], which once more proved the influence of stacking sequence on void formation.

2.2.5. Moisture. Due to the fact that the moisture absorbed during the storing is one of the reasons for void formation, the effect of moisture during processing on void formation is studied. The effect of dissolved moisture was studied by Grunenfelder and Nutt in [34]. An uncured pre-preg was conditioned at 70, 80 and 90% relative humidity. The Conditioned pre-preg was laid into quasi-isotropic laminates and cured by means of the autoclave processing. They found that with the increasing moisture content autoclave-processed parts remained void free as shown in Fig. 9, page 2308 in [34] and Fig. 5, page 1567 in [30]. Their findings confirmed the results reported in [35]. However, Gu *et al.* drew a different conclusion and claimed that a high humidity environment also increased the probability of void growth and gave a rise to high porosity for the same resin pressure [30].

2.3. Void reduction.

Two methods can be used to control the presence of voids in composites. One is to understand void formation mechanisms as mentioned above and another one is to develop effective methods for void removal to be discussed in this section of the paper.

The effect of fluid velocity on void formation was studied and used for void reduction in [15, 21, 17]. It was found that macro-voids tended to form during fiber impregnation at a low speed while micro-void formation was stimulated by a high resin velocity as shown in Fig. 3, page 1861 in [15]. Therefore, it was assumed that an optimal impregnation velocity was of great help to minimize void formation.

Improved pressure control at the vent was proposed for void reduction in [14, 16]. At the beginning of resin infusion, high vacuum was used to avoid air entrapment. High pressure used after the resin had saturated all of reinforcements restrained the resin evaporation. In this way, a CFRP material with lower void content was obtained.

As for the autoclave process, it was reported that mechanical vibrations helped to eliminate the voids when they were applied to the curing system of composite materials production [36, 37]. Muric-Nesic *et al.* found that a longer period of vibrations produced more efficient void deduction, grouping smaller bubbles into bigger and removing them as well as dispersing small bubbles [37]. The authors concluded that the vibratory energy provided a mechanism for migration and dispersion of the initial void. They also found that low frequency vibrations resulted in significant void content reduction by approximately 60% [38].

3. Effects on mechanical properties

Voids are always the potential locations of failure and cause discontinuity in the material properties of CFRP, which degrade the mechanical performance of CFRP. The loss of mechanical properties can occur in all CFRP structures, and tends to increase in frequency with structural complexity. The effect of voids on the mechanical properties of CFRP products has been the subject of many investigations for several decades. The mechanical properties of CFRP products are usually classified into two groups after taking into consideration the fact that CFRP materials are a combination of fiber and matrix. One group consists of fiber-dominated mechanical properties and another group includes matrix-dominated ones (see Table 1). As for voids, many studies pointed out that fiber-dominated mechanical properties were not significantly influenced by void presence, while matrix-dominated properties were strongly dependent on their presences [27, 39]. This is partially due to the fact that CFRP products are very sensitive to stress concentration and voids unfortunately influence stress distribution in CFRP products and lead to stress concentration, which finally results in a local failure.

Table 1. Effect of fiber and matrix on mechanical properties.

Mechanical property	Fiber-dominated	Matrix-dominated
Tension	Yes	No
Compression	Yes	Yes
In-plane shear	Yes	Yes
Inter-laminar shear	No	Yes

3.1. Void evaluation

Currently, a general consensus is that the mechanical properties of CFRP products decrease with increase of void content. Therefore, most of the reported studies on void analysis have focused on attempts to relate the mechanical properties of CFRP products to the void content.

One method is referred to as Mar-Lin criterion, and has been modified for the analysis of CFRP products containing voids [6, 40]. Other studies suggest torepresent the stiffness or strength reduction as a linear or second-order polynomial function of the void content [41, 42]. All research works report decreasing strength for higher void contents, and quantitative results demonstrate large scatter [6, 27, 33, 40, 42–47]. This may be caused by using different manufacturing processes to fabricate specimens with different void contents [48].

However, it should be noted here that trying to correlate void content with certain mechanical properties of CFRP products alone is far from being sufficient. It is very clear that during the manufacturing the processing parameters simultaneously affect the distribution, location, shape and size of the void. Each of these parameters causes a different effect on the mechanical properties of CFRP products. For example, a spatial void distribution is an important factor since it dictates the overall performance of CFRP a component [25, 27, 44, 48–50]. A single void present at the critical location could be more harmful than multiple ones present in the CFRP product. Besides, it was found that randomly shaped voids have more severe effects on the mechanical performance of a CFRP product as they can cause premature crack initiation [24, 44, 51]. Therefore, the influence of void shape should not be ignored when an accurate result is expected. In addition, the variation of distance between the voids was found to be more critical than the void shape and percentage porosity levels [46]. Lastly, a larger void has a more serious effect on bending modulus of CFRP products [45]. In other words, each of these factors has an effect on the mechanical performance of CFRP products and any unreasonable simplification will lead to a dangerous underestimation.

3.2. Influence on inter-laminar shear strength (ILSS)

Among the mechanical properties of CFRP products ILSS, a typical property dominated by matrix, is the most sensitive one to the appearance of voids. Olivier *et al.* found that there was a decrease of 15% in ILSS when void content increased from 0.3 to 6.8% for one type of specimens and the decrease increased to 35% for another ILSS with void content increasing from 1.4 to 6.8% [27]. In addition, they noticed that the longitudinal modulus as well as the longitudinal tensile strength was not affected by voids. However, the transverse properties were found to be extremely sensitive to the presence of voids.

Wisnom *et al.* reported a reduction in ILSS between 8 and 31% for discrete voids from 0.28 to 3.0 mm long [41]. They concluded that the commonly observed decrease in ILSS with increasing void content was caused by the combination of reduction in the cross sectional area due to distributed voids. The reduction in ILSS of CFRP products due to the appearance of voids was given as follows:

$$S(V_v) = S(0\%)((4V_v/\pi)^{1/2}), \tag{3.1}$$

where $S(0\%)$ is the theoretical ILSS for void-free CFRP product and V_v indicates the void fraction volume in a section of the CFRP product.

Costa *et al.* found a good agreement with the experimental results by using the above criterion (Eq. (3.1)) [6]. The authors reported that the carbon/epoxy laminates with void content above 0.9% had their ILSS decreased by the presence of voids.

Using the empirical exponential relationship Liu *et al.* found that in the range of 0 to 4%, each 1% increase in void content decreased ILSS by 9% and tensile modulus by 2% [28]. In 2006, these authors also reported that all the strength including shear strength, flexural strength and tensile strength showed a decrease with increasing void content, among which the decreasing percentage for ILSS was the largest as shown in Fig. 8, page 307 in [29].

In 2009, Zhu *et al.* claimed that ILSS decreased with increasing void content of their specimens [33]. But the void sensitivity was different due to the different stacking sequences applied, which indicated that stacking sequence affected the void formation and consequently the ILSS of CFRP products.

Although voids have a great effect on ILSS of CFRP products, ILSS could be insensitive to void content lower than 1%, which was pointed out by Costa *et al.* and Rueda, respectively, in [6, 52]. That is why 1% of void content for CFRP products is regarded as the limitation for many applications.

3.3. Influence on compressive strength

Since matrix stabilizes the fibers and prevents them from buckling in compression, the appearance of voids in a matrix affects the matrix strength and consequently the compressive strength of CFRP products. Suarez *et al.* investigated the effect of void content on the compressive strength of unidirectional carbon/epoxy laminates [53]. They found a roughly linear correlation between void content and compressive strength, with a reduction of about 40% for the void volume fraction of 4%.

Lower influence of porosity was found by Cinquin *et al.* for quasi isotropic carbon/epoxy laminates with a 14% reduction in the compressive strength for a void content of 11% [54].

Rueda pointed out in [52] that limited porosity levels (below 2%) could lead to a noticeable reduction in the compressive strength and this effect would be amplified for higher void volume fractions. Nevertheless, when the void content was relatively small, the difference between the effects of different void contents on compressive strength was not significant, as shown in Fig. 4.

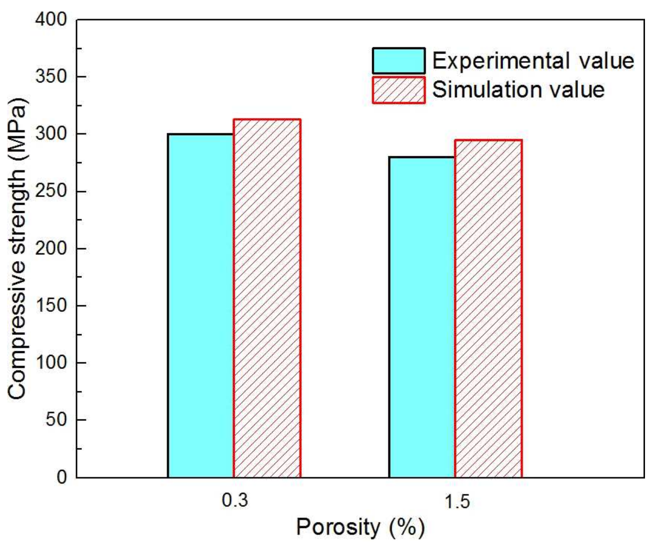


Fig. 4. Effect of void content on compressive stress (reprinted with permission from [47]).

3.4. Influence on flexural strength

Almeida *et al.* reported a good correlation between the CFRP strength and void content for the inter-laminar flexural strength [40].

Similarly to Olivier *et al.* [27], they found a reduction in both flexural modulus and bending strength of 20% and 28%, respectively, for the 14% void content.

Hagstrand *et al.* found that the flexural modulus and strength decreased by about 1.5% for each 1% of void up to the 14% void content level [55].

Zhang *et al.* showed that a general trend of the tensile, compressive, bending and inter-laminar strength of CFRP components decreased with the porosity increasing from 0.33% to 1.5% (as shown in Fig. 19, page 17 in [23]) [47].

Suhot *et al.* demonstrated that a 2% increase in void content reduced the flexural strength by 12.7% [39]. They assessed that void size was an important void characteristic.

Some further experimental studies have shown that with a 1% increase in void content, the flexural strength and flexural modulus could decrease by more than 5% [28, 33, 56–59].

3.5. Influence on fatigue strength

The presence of void also reduces the fatigue strength and durability of a CFRP material and makes it more susceptible to environmental conditioning and moisture absorption. Although CFRP products are theoretically not highly sensitive to fatigue, this situation changes due to the appearance of voids.

Fatigue properties were in general more affected by the void content than static properties. Almeida and Nogueira Neto carried out a four-point bending test on $[0/90]_{12}$ carbon/epoxy laminates and found that the static strength was not influenced by a 3% void content but the same void content had a detrimental effect on fatigue strength [40].

Bureau and Denault found that different void contents led to a shift of the S-N curves without a change in their slopes, indicating a reduction of fatigue life with an increase in void content [60].

Damage evolution under bending fatigue was also investigated by Chambers *et al.* [49] for unidirectional CFRP products. They noticed that, by varying the void content from 1.6 to 3.1%, the fatigue life changed from 2000 to 106 cycles. The authors concluded that the voids played a fundamental role in the fatigue life when they were located in the inter-ply region where delamination occurred. They also reported that for void contents up to 2% there was no obvious negative effect of voids on fatigue life but for higher void contents (>2%) fatigue performance decreased, as shown in Fig. 11, page 1395 in [49].

For wind turbines, the effects of voids on the CFRP flexural fatigue have been shown to be dependent on void geometry and distribution [61, 62].

3.6. Influence on other properties

Asp and Brandt [63] investigated the effects of pores and voids on the interlaminar delamination toughness of carbon/epoxy laminates by means of static Mode I, Mode II and mixed mode fracture tests. The results were inconclusive due to the large scatter.

Olivier *et al.* [27] found that Mode I fracture toughness depended very much on the void volume fraction. They reported a reduction of 22% in G_{IC} for a 5% void content.

Vajari *et al.* found that porosity (in the range of 1–5%) led to a large reduction in the transverse strength by numerical studies [64].

Besides the tensile strength, the effect of voids in low velocity impact and in after impact strength was negligible [52]. This was due to the fact that the effect of an impact was masked by the damage mechanisms induced by the impact itself.

Selmi found that the gap between the normalized transverse Young modulus and the normalized longitudinal shear modulus for composites with and without 2% of randomly oriented voids increased with increasing carbon fiber volume fraction [65]. It might reach 20% for a 60% volume content of carbon fiber.

Tensile strength was reported to relate to local impregnation velocity as shown in Fig. 19, page 1867 in [15]. Macro- and micro-voids were observed to affect the tensile modulus in different manners was observed, which was assumed to indicate that the formation of macro- and micro-voids had different impacts on the mechanical properties of CFRP.

Voids have a significant influence on the stress distribution in the matrix, which leads to stress concentration particularly around the end caps and the longitudinal side of the voids [66]. Additionally, void length was found to have an essential effect on the compression failure modes.

4. Conclusions and discussion

According to the studies summarized in this paper, the following conclusions can be drawn.

- Many factors contribute to void formation, including the curing pressure, temperature, resin system and so on. Although the reported studies show that a curing pressure plays an important role during void formation, the other factors should not be ignored. Moreover, these processing parameters affect each other, which may be one of the reasons that causes the scatter in the reported studies. On the other hand, careful selection of processing parameters helps to minimize void formation.

- Voids have a great effect on the mechanical properties of CFRP products, especially the matrix-dominated properties. But the fiber-dominated properties are affected by the appearance of voids as well.
- Despite the fact that void content has been used as a major evaluation factor for many years, the shape, size and distribution of voids should also be considered. Therefore, a new representation method for void evaluation should be proposed in the future. To gather the related parameters of voids, including shape, size and distribution, X-ray-based nondestructive detection method is recommended, which has shown a promising result on void detection.
- Some of the reported results have shown great variety, which may be due to the adoption of different values of curing pressure, curing temperature, resin system, stacking sequence and so on. Therefore, it seems urgent to establish standard processing rules for comparison. A benchmark for void study would also be a great contribution to void analysis.

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