Chapter 10

# Damage Prediction in Woven and Non-woven Fabric Composites

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**Abstract**

This chapter presents a step-by-step review on different damage prediction approaches for woven and non-woven fabric composites. First, the characteristics of woven and non-woven fabrics are distinguished one from another, suggesting more complex analyses required for non-woven fabrics. Then, the subsequent sub-sections are geared toward a comparison of different approaches utilized in predicting the mechanical behavior and damage mechanisms of these composites at various material scales including micro, meso, and macro. The merits and demerits of each approach with regard to practicality, accuracy, effectiveness, and characterization expense are discussed. Moreover, using recent experimental evidences, the chapter aims to highlight a number of inherent complexities in the interlaced architecture of woven composites, which may not be precisely taken into account by the damage models originally developed for non-woven and unidirectional composites. Finally, two illustrative examples on the effect of the aforementioned complexities on the mechanical behavior of woven composites are presented in more detail, through some recent works of the authors.

**Keywords:** Fabric reinforced composites, Damage mechanisms, Prediction models, Advanced characterization

## 1. Introduction

Several decades ago, composite materials were introduced with a great potential to replace conventional monolithic materials, primarily metals, due to two main features:

- Much higher ratios of stiffness and strength to weight
- Anisotropy of material properties, providing designers with more flexible design options

Since the dawn of composite materials (1937), "unidirectional" (UD) fiber reinforced composite materials caught most of the designers' attention for several years, primarily due to their high specific stiffness ratios as well as simplicity in their analyses/design. Nevertheless, woven fiber reinforced composites gradually became a decent alternative to traditional UD composites in specific industries [1]. Woven fabric reinforcement in essence can be defined as interlaced warp and weft fibers in a repetitive pattern or weave style such as plain, twill, satin, etc. Woven composites can enjoy numerous inherent characteristics—all of which arising from their interlaced fibrous structure [1]:

- Laminated composites comprised of UD architecture are often inclined toward experiencing delamination, which in turn can decrease their stiffness and yield low damage tolerance. Instead, interlaced yarns in two directions of woven fabric reinforced composites can decrease the mismatch between laminate layers, and hence helping the material system resist de-bonding and its propagation in a superior manner.
- The undulation of yarns, resulting from the interlacing yarns, induces an out-of-plane reinforcement state in woven textile composites, whereas UD composites generally suffer from a weak resistance through the thickness direction.
- The manufacturing process of woven fabric composites is generally easier than the UDs. This is mainly because of the yarns entanglement, easing the draping and molding process of the material for producing near-net shapes.
- Woven fabric plies, due to their bi-directional reinforcement, can show a much more balanced behavior than the UDs under complex loading modes in service.

In addition to woven fabrics, there exists another main type of fabric reinforcement known as 'non-woven' fabrics, which also include 'felts'. Non-woven fabrics are sheets or web structures comprised of chopped or long fibers or filaments arranged in a rather disordered architecture and consolidated by bonds of different nature, such as chemical, mechanical (e.g., stitching), or thermal bonding, rather than geometrical weaving or knitting. According to this definition, the distinct differences between woven and non-woven fabrics are the fibers arrangement at the microstructural level and the type of bonding. Woven fabrics have an ordered architecture of fibers interlaced to one another, whereas there is more randomness in the fibrous architecture of non-woven fabrics. Recently, in light of lower processing cost of non-woven composites, and easier recyclability in some cases, the use of these materials is being increased in several industrial applications such as fireproof layers, thermal insulations, ballistic protections, liquid-absorbing textiles, and geotextiles for soil reinforcement [2]. Owing to the aforementioned inherent geometrical differences between woven and non-woven fabrics, their mechanical performances are also expectedly different. In general, woven composites enjoy higher stiffness and strength in comparison with non-woven felts. However, the ultimate deformation and absorbed energy values in non-woven fabrics are often higher than woven fabrics [2].

Thanks to defined standards by most governments and related safety authorities, risk-sensitive industries in general, and aerospace and transportation in particular, as the main sectors of the composite world, are expected to satisfy certain requirements before a product can be

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brought to service. By flourishing the use of composites more and more, so crucial is the possession of a comprehensive knowledge on their underlying damage mechanisms upon which the ultimate load bearing capacity and deformation of structures can be predicted. As a matter of fact, the design of a composite structure with highest safety and at the same time the lightest possible *weight* cannot be accomplished without a profound knowledge on its damage behavior. Regarding the damage modeling of composite materials, to date there have been much more research activities in the area of UD composites, rather than woven and non-woven fabrics. As an example, according to the World Wide Failure Exercise [3], there are nearly 20 failure theories derived for UD composite materials, while there is a very limited explicit failure criterion specifically developed and standardized for woven composites. Actually, using some assumptions and modifications, the common failure models of UD composite materials, for example the maximum stress criterion, are being used by some practitioners for the damage analysis of woven materials. This practice is despite the fact that none of such failure theories has been originally developed to mimic the woven nature of reinforcing material in consolidated laminate. The fact is, although woven composites are endowed with some advantages in comparison with UDs on account of their enhanced fibrous architectures, some intrinsic complications can cause their analysis to be cumbersome and very different from UDs. These complexities are briefly introduced in this section and will be further discussed in the next sections of the chapter. One of these difficulties is the change in cross-section of woven yarns over their longitudinal axes. Another one is that fibers are not straight in woven yarns similar to fibers in UD tows. In fact, yarns can have in-plane waviness (misalignment) and out-of-plane waviness (crimping) in woven laminates, which considerably affect their tensile and bending behaviors. Moreover, interaction between the warp and weft yarns may affect the effective mechanical behavior of woven laminates, especially under multi-directional/combined loading modes, similar to its significant effect on the mechanical behavior of dry fabrics. Furthermore, owing to a cellular reinforcement architecture, failure modes such as matrix cracking is restricted between weave cells in woven composites and cannot propagate as fast as it would in UDs. Another point is that the interlacement of yarns can cause local stress concentrations at meso-level. More severe complications come in the behavior of non-woven fabrics due to their rather random architecture and complex contact between fibers. Fiber re-orientation, fiber sliding, non-linear bond failure, fiber fracture, and continuous rearrangement of fibrous network are among other difficulties encountered in the analysis of non-woven fabrics [2].

The rest of this chapter attempts to review the methods employed by different researchers to investigate the mechanical behavior of woven and non-woven fabric composites in general, and their damage mechanisms in particular. Benefits as well as disadvantages of each approach are discussed by relating to the above-described inherited complexities in fabric composites. In addition, the validity of presumed assumptions for each approach is argued. For woven composites, different approaches will be discussed in sub-sections 2.1.1–2.1.3, and the approaches employed to predict the mechanical behavior of non-woven fabrics, which are methodically similar to those of woven composites, are reviewed in section 2.2. Thereafter, the above-addressed incompatibility of previous damage models of UDs to accurately anticipate the mechanical behavior of fabric composites is assessed. In particular, it is argued that owing to complex reinforcement architecture in woven composites, new enhanced damage models need to be driven. In order to further underscore this need, some recent experimental evidences by the authors regarding the influence of in-plane and out-of-plane waviness of yarns upon the mechanical behavior of a typical woven composite is presented. The last section of the chapter outlines the main conclusions and the anticipated future work developments.

## 2. Damage modeling approaches for fabric composites

Preparatory to discussing the damage mechanisms of woven and non-woven fabrics, a definition for an appropriate damage model should be provided. Generally, a comprehensive and accurate damage model for a given material would embrace three features:

- Damage initiation: Exploiting precise and reasonable failure criteria to predict the onset of various failure modes is the primary part of any damage model.
- Degradation of material properties: On account of any damage in a material, it cannot provide stiffness and strength as high as its undamaged state. Anticipating a reasonable pattern to reduce the mechanical properties of the material upon damage is another critical aspect of a full-scale damage model.
- Damage propagation: How an induced damage grows is perhaps the most controversial part of any damage model. Forecasting the rate of damage growth with an acceptable accuracy imparts the post-damage behavior and tolerance of a manufactured structure/product during service.

The studies investigating damage in woven and non-woven fabric materials can be classified in different ways. One categorization may be with respect to the group of studies on each of the three aforementioned features of a damage model. Another classification is based on the investigations methodology. Researchers have performed analytical, numerical, and experimental methods in order to study the damage behavior of fabric composite materials. The numerical and analytical studies are in turn divided to micro, meso, and macro. The latter type of classification is the one opted here for the subsequent review sections.

### 2.1. Damage models for woven fabric composites

#### *2.1.1. Micro/meso level analyses*

Despite the fact that composite materials are predominantly regarded as homogeneous orthotropic materials, notably in industrial projects, they are not as homogeneous as conventional materials such as metals. Composites are comprised of fibers and matrix constituents and therefore the mechanical properties of different points of the material medium are not necessarily the same. In fact, it is this specific feature of composite materials that distinguishes their global behavior. As an illustration, when a visible macro-damage is observed in a composite specimen under loading, failure has already initiated and propagated in the micro/meso level of the specimen before it appears at macro level. As a consequence, one of the ways

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to study the failure mechanism of fabric composite materials is to conduct an investigation into the micro/meso levels. However, studying full scale structures/specimens at these levels is more arduous and expensive in comparison to the macro level. In order to carry out the micro/meso level analyses of composite materials in a cost-effective manner, the smallest segment of a whole specimen is sometimes defined such that it is the representative of the whole specimen. That is, the whole specimen should be reproducible by repeating this representative volume element (RVE). Homogenization—the main basic rule in the RVE approach—is then employed to define the effective mechanical properties of the RVE based on the mechanical properties of its constituents, namely fibers and matrix. The effectiveness of the micro/meso-level investigation for woven composite materials is deemed to be more, when compared to unidirectional composites, in that the micro-structure of woven architectures is more complicated and may not be idealized at macro-levels.

The woven composite RVEs can be mainly studied in two ways. The first method is to model yarns in warp as well as fill directions and matrix in a detailed numerical model with shell or solid elements. In this approach, the yarns and matrix are considered explicitly. In one of the first study of this kind, Blackketter et al. presented a meso-level model for woven composite materials using solid elements [4]. In their simulations, the mechanical properties of yarns, which included fibers and resin, were found based on the micromechanical homogenization approach and the mechanical properties of constituents. The volume fraction of fibers in the yarns and in the unit cell was selected 70% and 60%, respectively. The failure occurrence in the matrix, which was considered isotropic, was based on a maximum stress criterion. In addition, damage degradation was taken into account by decreasing the corresponding Young's modulus of the Gaussian integration points in an element by 99%. Regarding the yarns modeled as orthotropic materials, two failure modes in the longitudinal and transverse directions were assumed. The results of experimental and numerical studies were rather comparable.

In another study, Tang and Withcomb assumed a failure criterion and a linear degradation model for different woven architectures in order to compare their damage mechanisms [5]. They modeled warps, wefts, and matrix pockets of an RVE in a detailed 3D fashion. The maximum stress failure criterion was utilized. The obtained results showed that the weave architecture can have a considerable impact on the composite's progressive damage behavior, even if the volume fraction of fibers, tow waviness, and tow cross-sections of the specimens were the same. Jia et al. established a micro-meso scale model for the repeating unit cells of a 3D woven composite material, in which there were yarns in three principal directions [6]. The yarns in the meso level simulation were composed of repeating micro representative unit cells (RUC) consisting of fibers and matrix. The maximum strain and stress values were monitored as the failure criteria for the damage in the matrix and fibers. As to post-damage behavior, they presumed that the corresponding stress becomes zero instantly. A quadrilateral cross section was employed for the yarns. The results for one tensile testing demonstrated that there is an agreement regarding the ultimate strength prediction by the model; however, there were disagreements between numerical and experimental results at each time step (i.e., different stages of deformation before the final failure). In another research project by the same authors, the behavior of woven composite materials under three-point bending was investigated at a multi-scale (micro-meso-macro) level [7].

In each of the aforementioned studies, only a fabric cell was modeled, as a periodic boundary condition was used instead of repeating cells to create the whole specimen geometry. In general, there are two types of periodic boundary conditions known as parallel and series models. In a parallel model, it is assumed that the displacement of all constituents (cells) is the same and the load is shared between them. On the other hand, the stress is presumed to be the same in all cells in a series model, and the general displacement is the sum of that of each cell. In order to avoid such boundary assumptions, some researchers have opted to create the whole specimen meso-model by reproducing a large number of cells adjacent to each other. A good example of such approach is the simulation conducted by Chandekar and Kelkar [8]. Making use of LS-DYNA, they investigated the low velocity impact of glass and carbon woven composite materials [8]. The mosaic pattern was chosen to repeat the unit cells so as to produce the whole plate geometry. Although comparable results were observed between numerical and experimental results, running such simulations normally takes a considerable time, comprising their effectiveness for large scale industrial simulations.

In order to reduce computational time in meso-level modeling of woven composites, a second RVE methodology has been introduced. In this approach, the RVE is divided into several sub-cells, instead of a great number of elements. Where one level of homogenization was considered in the first RVE modeling approach, two levels of homogenizations are performed in the second approach; the first of which is to find the general mechanical properties of sub-cells and the second is to determine the general mechanical behavior of the whole cell. The first research in this area was performed by Ishikawa and Chou [9]. Employing the classical laminate theory, they studied the elastic behavior of woven fabric materials in three models, including mosaic, undulation, and bridging models [9]. In the mosaic pattern, the fiber continuity and its crimping were not taken into account. However, these factors were considered in the undulation model. One of the main limitations of this model was that two UD layers were assumed instead of one interlaced layer. After this work, some researchers attempted to conduct investigations into the failure behavior of woven fabric materials using the sub-constituents method [10–12]. In one of the latest papers in this area, Li et al. predicted the stiffness matrix, strength, and damage evolution of woven fabric materials using Abaqus [13]. They used parallel-series assumption for the two-level homogenization. Six failure variables referring to six failure modes, including longitudinal, transverse, and out-plane failures, besides shear failure in 12, 23, and 13 directions, were taken into account. The maximum stress was chosen as the failure criterion of both fibers and matrix. The numerical results were comparable with the experimental data of tensile tests on a glass epoxy woven composite.

Although using RVEs as representatives of woven fabric materials could help designers predict the general behavior of these materials with some accuracy, this method relies on some limiting assumptions. For instance, a common assumption is that fibers and matrix have perfect contact with each other. In other words, the interface between yarns and matrix is assumed to be bonded perfectly under arbitrary deformation conditions. In reality, however, voids which arise during manufacturing processes are inevitable. On top of that, even by assuming perfect curing/consolidation, the genuine contact between fibers and matrix is similar to a 'tiebreak' contact, rather than a tied contact. In a tiebreak contact, components are bonded to each other until an ultimate interface stress is reached [14], which debonds fibers and matrix. As stated earlier, another drawback of the RVE approaches may be that the simulations in micro as well as meso levels normally takes a great amount of time/cost; therefore, they are not always feasible to use for industrial applications. The last, and perhaps the most debatable, point is that in reality the failure starts in one point of a specimen and propagates to other points, whereas it is assumed in the RVE approach that when a failure mode occurs within one RVE, it arises in all the RVEs. In other words, damage localization cannot be captured in most RVE approaches. The most useful information that can be obtained from such analysis, however, is the extent of stress concentration in the meso/micro level due to the specific architecture of woven fabric materials; specially knowing that the stress applied to the composite constituents can be much higher than the global stress applied to the specimen at macro level [15].

*2.1.2. Macro level analyses*

As a general characteristic, macro level analyses do not take into account the micro failures in the composite specimens. Although macro level analysis of damage mechanism in woven fabric materials is not as complex as its micro/meso level counterparts, it is more practical (cost-effective) for large scale simulations. The published works in this area can be divided into three categories as follows.

*2.1.2.1. Failure criteria-based approach*

In this method, specific relationships based on either stress or strain components are introduced for the onset of failure modes. One fashion for the presentation of this method is the use of a single relationship to represent all the failure modes collectively. A case in point is the Tsai-Wu failure criterion [16] which offered a response surface for damage in stress or strain space. This approach is not able to distinguish between individual failure modes. Moreover, it is not meant to consider the degradation mechanism of composites. In order to propose a precise degradation mechanism, the induced failure modes have to be identified individually so that the corresponding stiffness coefficients can be decreased gradually.

There is another presentation type under this approach which offers a distinct relationship for each failure mode. Perhaps the most popular models of this kind are those proposed by Chang-Chang [17] and Hashin [18]. Nevertheless, all of the aforementioned failure criteria have been developed for UD composite materials, rather than woven fabric composites. In these failure criteria, the authors have assumed that failure in the longitudinal and transverse directions correspond to failure in fibers and matrix, respectively. As an example, Table 1 [14] shows the introduced failure criterion for each failure mode by Chang-Chang. For the Hashin failure criteria, $\beta$ in the first equation is 1. According to this table, the failure modes of UD composites are classified as compression as well as tension in both fibers and matrix (longitudinal and transverse) directions, whereas in woven composite materials, fibers (wefts and warps) are spread in both longitudinal and transverse directions.

| | |
|---|---|
| **Tensile fiber mode** | $e_f^2 = \left(\frac{\sigma_{aa}}{X_t}\right) + \beta \left(\frac{\sigma_{ab}}{S_c}\right) - 1 \begin{cases} \geq 0 & failed \\ < 0 & elastic \end{cases}$ |
| **Compressive fiber mode** | $e_c^2 = \left(\frac{\sigma_{aa}}{X_c}\right)^2 - 1 \begin{cases} \geq 0 & failed \\ < 0 & elastic \end{cases}$ |
| **Tensile matrix mode** | $e_m^2 = \left(\frac{\sigma_{bb}}{Y_t}\right)^2 + \beta \left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1 \begin{cases} \geq 0 & failed \\ < 0 & elastic \end{cases}$ |
| **Compressive matrix mode** | $e_d^2 = \left(\frac{\sigma_{bb}}{2S_c}\right)^2 + \left[\left(\frac{Y_c}{2S_c}\right)^2 - 1\right]\frac{\sigma_{bb}}{Y_c} + \left(\frac{\sigma_{ab}}{S_c}\right)^2 - 1 \begin{cases} \geq 0 & failed \\ < 0 & elastic \end{cases}$ |

**Table 1.** Chang-Chang failure criteria [14].

Another notable point is that in the former type of 'surface' failure criteria (also called failure 'envelope'), some terms of both longitudinal and transverse stresses appear in the corresponding relationships, meaning that the stress values in both principal directions can accelerate the failure occurrence. On the other hand, in the second category, no terms of transverse (longitudinal) stresses are observed in the presented relationship corresponding to the failure in longitudinal (transverse) direction, as shown in Table 1. In other words, the latter technique of failure introduction assumes that the transverse stresses do not affect the failure in the longitudinal direction, and vice versa. The validity of such presumption should be challenged particularly for consolidated fabric composites, as there have been recent evidences of influence of coupling between warp and weft yarns in dry and coated fabrics [19–22] as will be further expanded on in section 2.1.3.1 Furthermore, as indicated earlier, both of these modeling types can forecast the initiation of damage and not the damage growth. In fact, after fulfillment of such relationships, the corresponding stiffness coefficients decrease to zero.

Recently, Materials Science Corporation (MSC) presented a model for woven composite materials by generalizing the Hashin failure criteria [14]. They assumed tensile and compression in both warp and fill directions, crushing failure, shear failure due to matrix cracking without fiber breakage, and tensile matrix failure in the out of plane direction. However, for failure in the warp and fill directions—the most common and predominant failure mode in woven composites—the relationship was analogous to that of Hashin's. That is, the effect of stress in the second main direction is not seen in the relationship for the first main direction.

*2.1.2.2. Plasticity-based approach*

Unidirectional composite materials are predominantly known as brittle materials showing an elastic and linear response until failure. However, woven composite materials can show a non-linear response even in the early stage of a tensile test in the fibers' direction [23]. Some facts, such as wavy architecture of woven composites, visco-elastic behavior of matrix, and matrix cracking, can be postulated as the reasons of such non-linearity. Although earlier studies [23] showed that matrix cracking in woven composites can partially cause a non-linear tensile behavior, there has not been a full-scale investigation into discriminating all different sources and understand their effects. One of the easiest modeling methods to take the non-linear behavior of woven composites into account is the plasticity approach, in which the non-linear behavior of the composite is equivalently modelled as a plastic material behavior, regardless of the reason of non-linearity. In the first study in this area, Hill introduced a plastic model for anisotropic materials [24]. Vaziri et al. proposed a comprehensive plasticity model for fiber reinforced composite plies based on a rate-independent orthotropic plasticity theory [25]. In this method, a relationship known as flow rule is considered between the effective strain and the effective stress. The coefficients of the flow rule are obtained using several tensile tests. Although this approach is very suitable to prediction loading regimes, it is not as accurate for events containing loading and unloading regimes, such as impact events, especially after the occurrence of some damage. The loading-unloading response of damaged woven composites has not been fully characterized in the literature yet. Each of the aforementioned non-linearity sources in woven composites probably has a different influence on the unloading behavior of these materials. In addition, in woven composites under tensile loading, the first failure mode is matrix cracking, decreasing the stiffness in a non-linear manner and causing a non-linear global response as illustrated in Figure 1 [23]. However, there is a fact known as 'crack saturation' in which crack growth is saturated and stopped. After crack saturation, a linear response is seen until yarn breakage. As a result, in some cases after damage initiation, some linear responses are observed in reality, which cannot be modeled by the plasticity approach. Another point regarding the limitation of the plasticity approach is that the behavior of composite materials in general, and their stress-strain responses in particular, under compression are not the same as that of tensile loading. This fact can be interpreted in a way that fiber yarns in composites, which may be comparable to thin beams, are more endangered with compression loading—buckling—rather than tensile loading. As a result, the ultimate compression strength of composite materials is predominantly less than their maximum tensile strength [26]. Also, the non-linearity in tensile loading of textile composites does not necessarily exist in compression loading. Hence, the plasticity method may not be fully applicable to simulate the behavior of woven composites under real-life loadingssuch as crashes in which some regions of the structure undergo compression. Finally, the effect of stress in one yarn direction upon the failure in the other yarn direction (coupling effect) cannot be considered in the plasticity approach.

*2.1.2.3. Continuum damage mechanics-based approach*

The continuum damage mechanics covers the initiation as well as propagation of various failure modes, including matrix cracking, delamination, and fiber fracture under tension as well as compression. This approach was introduced by Kachanov [27] and developed for composite materials by Frantziskonis [28]. Basically, the method employs a set of damage variables each of which representing a certain failure mode and varying from zero to one, covering no damage, partial damage, and complete damage states in a material element. Frantziskonis also defined the damage variable, $r$, as the ratio of damaged volume to the total volume. It was assumed that the strain for the damaged and undamaged part is the same, and then the stress was calculated employing the mixed rule.

In another work under continuum damage mechanics-based approach, Feng et al. introduced a damage model for woven fabric materials [29]. Due to the stress concentration in textile

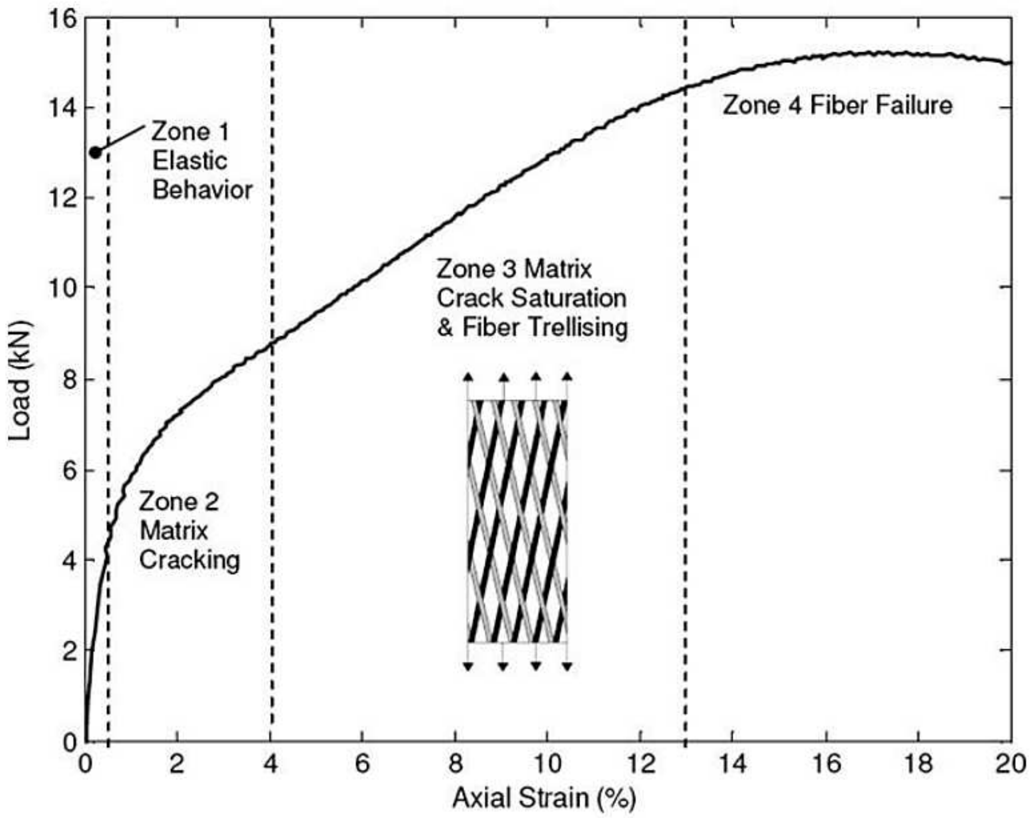


**Figure 1.** Tensile behavior of a woven composite sample [23].

composites arising from their complex fibrous architectures as proven in the micromechanical approaches using FEM [15], such materials can experience damage in early stages of deformation. Therefore, Feng et al. employed a stress variation factor (SVF) to correct the stress value by multiplying the nominal stress by the defined SVF. In their study, a woven lamina was assumed as two unidirectional (cross-ply) layers. Hashin failure criteria were utilized to predict the damage occurrence in each ply. For degradation mechanism, the corresponding stiffness coefficients were instantaneously reduced to zero. They compared the numerical and experimental results of a transverse compression test—punch test—on a woven composite specimen. The results were comparable in most cases.

Ladevaze and LeDantec introduced a continuum damage model for UD composite materials [30]. They wrote the strain energy based on the stress, stiffness, and damage variables of materials. Thereafter, driving forces, each of which being associated with a certain damage variable, was obtained by taking the derivative of strain energy with respect to damage variables. In fact, the damage evolution was based on such driving forces. In two subsequent investigations [31, 32], this approach was generalized for woven fabric materials. For instance, Johnson presented a 2D damage model that was able to predict the elastic failure in the warp and weft directions and the elastic-plastic in-plane shear failure for matrix [31]. Johnson used a linear relationship for the damage evolution based on the driving forces. In addition, that work employed a power law function to consider plastic hardening functions for cyclic loads.

The required parameters for the model were found using a tensile test. The damage model was implemented in an explicit finite element code in order to compare with the experimental results. In low velocity impact tests, in which there was considerable delamination failure, there was a substantial difference between numerical and experimental results, as shown in Figure 2.

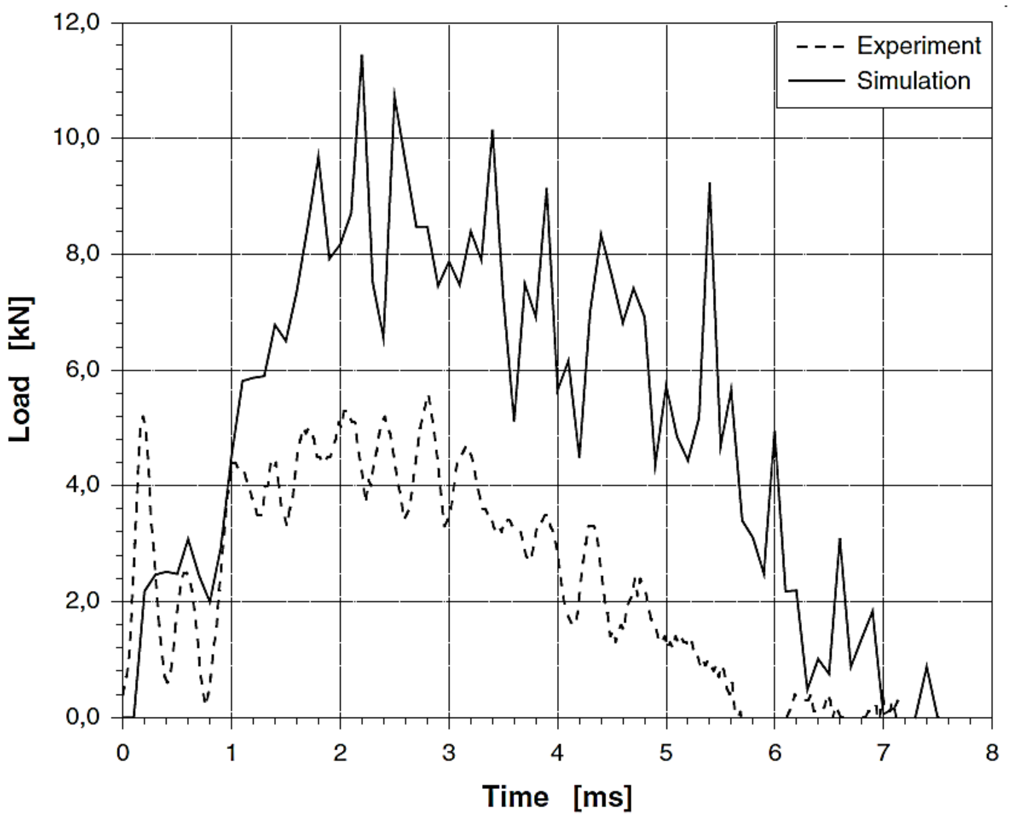


**Figure 2.** Comparison between numerical and experimental impact results [32].

Another research group introducing a damage model for woven composites is Iannucci and co-workers [33–35]. Iannucci et al. developed a progressive damage model for woven glass fiber-epoxy composite laminates and implemented it in a finite element code [33]. Their model was valid for shell elements with plain stress assumption. In addition, the proposed model was applicable to situations where there was no considerable damage, for example delamination, in the specimen. They postulated two unidirectional layers instead of one woven layer and found the Young's modulus and other mechanical properties required for modeling. Damage parameters varying from 0 to 1 were allocated for two types of failure modes, including matrix cracking and fiber fracture. The employed failure criteria, however, had been originally developed for unidirectional composite laminates. They also eliminated the terms of shear stresses in the employed failure criteria. A significant point of their work was that they defined an advanced model for damage propagation and degradation mechanisms, in that the rate of damage growth was proportional to the extent of damage and the value of corresponding failure criterion. However, one of the drawbacks of the model was that the damage growth rate could increase infinitely. The latter aspect of the model may not be reasonable on account of two facts:

- The maximum damage growth rate would be the stress wave speed in the material [33].
- Because of the crack growth saturation, as discussed before in section 2.1.2.2, the crack propagation cannot continue infinitely; it is restricted between the cells of weave architecture.

In the follow-up studies [34, 35], these authors introduced new failure modes in their originally developed model. Also, they made some efforts to distinguish between compression and tension failures. The presented damage model was rather accurate when the damage extent was not considerable. On the other hand, when there was a significant damage in the specimen, deviation between the model and experimental results was rather notable.

One of the latest research activities presenting a damage model for woven composites was performed by Cousigne et al. [36]. Employing LS-DYNA, they wrote a subroutine for woven fabric materials assuming a non-linear material behavior. Ramberg-Osgood equation [37] was exploited in different directions, covering longitudinal, transverse, and in-plane shear deformations. Effective macro-mechanical properties were determined based on tensile tests, and maximum stress failure criteria were chosen for damage initiation. Four post-damage models were considered as depicted in Figure 3. The force-displacement curves in Figure 4 demonstrate that the numerical results were not in a full agreement with the experimental data.

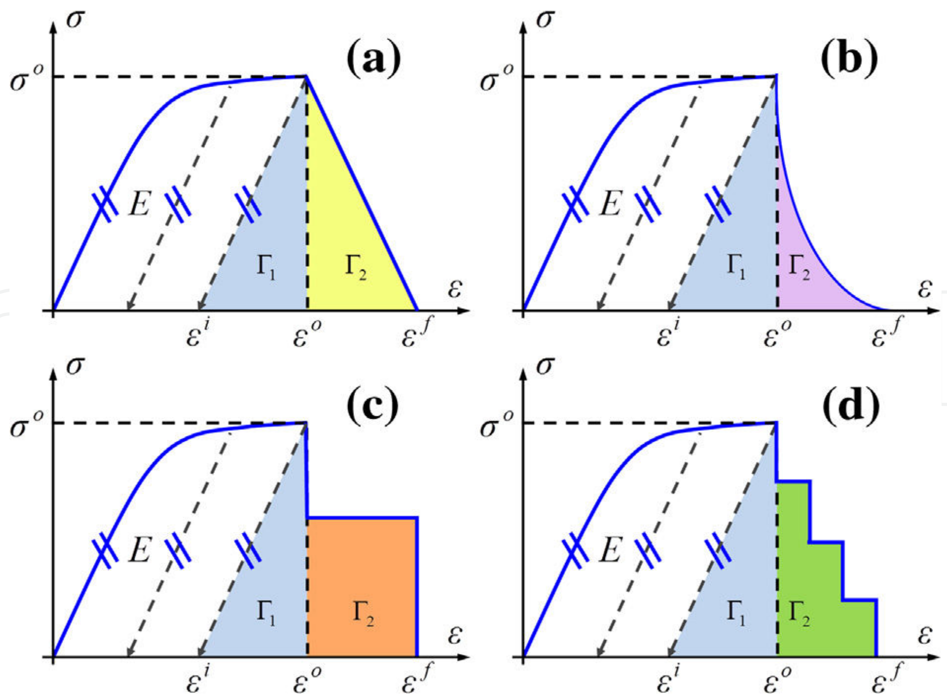


**Figure 3.** Four post-damage models for woven fabric materials: (a) linear damage, (b) non-linear damage, (c) constant stress level, (d) step-based material degradation [36].

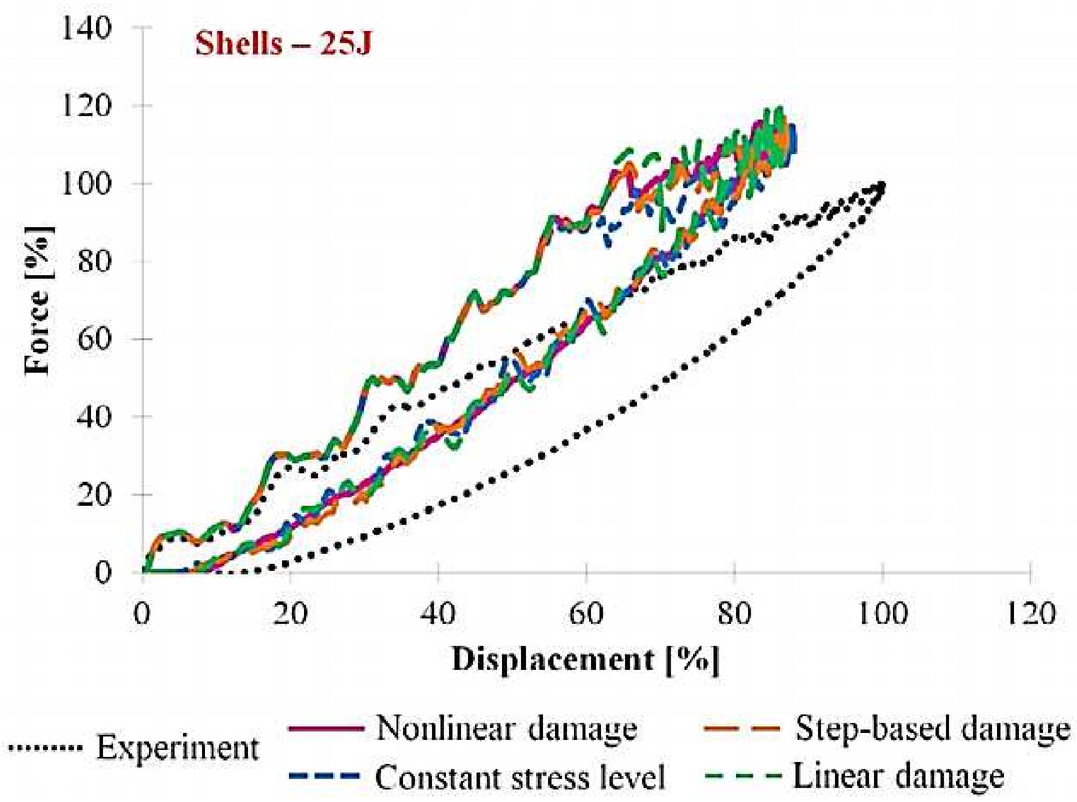


**Figure 4.** Force–displacement curves of 25J impact on a woven composite specimen [36].

Other researchers have aimed to use the pre-defined material models in commercial finite element programs to predict the macro-behavior of woven composite materials. A case in point is the study on low-velocity impact of thermoplastic woven composite specimens by Brown et al. [38]. They conducted an investigation into the applicability of MAT 162 of LS-DYNA material library—one of the most advanced material models for damage initiation and propagation in composite materials [14]—for the impact modeling of woven composite materials. At first, the parameters of MAT 162 were found using tensile tests on the woven specimens. Thereafter, the obtained parameters were used in impact simulations. Results showed that the identified damage model could not lead to highly accurate predictions against actual impact test data. In other words, the results again showed that the failure behavior of woven composite materials is more complicated than UDs and the original damage models need modifications.

*2.1.3. Experimental studies*

There have been several studies in the literature encompassing experimental research on woven composite materials. To illustrate a few, the compression behavior of woven fabric materials was investigated by Song et al. under quasi-static and high strain rate loading, employing a split Hopkinson bar [39]. The obtained results demonstrated that regardless of strain rate, the predominant failure mode was shear mode, while delamination happened only at high strain rates. Another category of most cited studies in this area links to the papers presenting differences between unidirectional and woven fiber reinforced composites. For instance, Evci and Gulgec performed an experimental study to find the difference between the impact behavior of thermoplastic woven and unidirectional laminates with the same fiber/matrix materials and thickness [40]. They introduced plain weave composites as an outstanding replacement for UDs in dynamics applications, owing to the fibers woven architecture that confines the damage. In addition, these materials were found to be more sensitive to strain rate, that is, their ultimate strength rises more substantially as compared with UD materials under high-strain rate loadings, mainly due to their higher visco-elasticity. Another article in this area is the study on the delamination modes I and II as well as impact resistance of woven fabric composite materials, performed by Kim and Sham [41]. Their results showed that woven composite materials are superior in comparison to UD composite materials under the above fracture modes and impact resistance criteria.

Mallikarachchi and Pellegrino endeavored to introduce the most elaborated failure criteria for symmetric two-ply woven carbon fiber reinforced plastics, by conducting numerous experiments [42]. In the first step, they used the Karkkainen relationship for failure occurrence including terms based on three forces and three moments applied to an element. This single equation is similar to the first presentation approach of failure criteria (section 2.1.2.1), which presents a surface for failure onset, and is not able to inform which type of failure arises in the sample. Tension, compression, shear, bending, and twist tests were performed with various lay-up configurations so as to find unknown constants of the utilized relationship/surface of failure. For example, [+45/-45] specimens were subjected to uniaxial testing and bending testing, separately, to induce shear and twisting modes, respectively. After identifying the unknown coefficients, they did several follow-up tests as combinations of five aforementioned loading types, in order to ensure that the presented model is reliable. However, the failure envelop relationship was not valid for some of the combined loading tests. Hence, instead of one equation for all the failure modes, they defined three failure modes, including in-plane, bending, and combined in-plane and bending, based on the three forces and three moments applied to the material element. The results showed that these failure criteria are valid for combined loadings. However, in the above approach, the final failure of woven composite was of interest and there was no identification of the first failure mode—matrix cracking—which decreases the stiffness of the material structure. In other words, such models are very reliable for prediction of catastrophic damage in textile composites but not for first-failure and progressive damage. In addition, although three relationships for failure of in-plane, bending, and combined loadings were considered, they cannot distinguish between individual failure modes under each type of deformation. Finally, the introduced relationships are based on the applied moments and forces, making the failure prediction analytics rather difficult for implementation in user-defined FE subroutines.

#### *2.1.3.1. Effect of loading modes and yarns interaction*

Generally speaking, among different deformation modes, the uniaxial behavior of materials has been investigated most. Woven composite materials are not an exception to this. However, the design of a targeted composite structure should not be based on the results of uniaxial tests only. This is because in sensitive events, such as a crash, structures experience different loading modes *simultaneously*, including tension, compression, and shear, in different directions. As an illustration, in an impact testing on a rectangular composite specimen, the elements in upper and lower parts of the material system may undergo biaxial compression and tension, respectively. Although conventional materials which have the same properties in all the directions should have almost the same properties (e.g., Young's modulus) under uniaxial loading or combined loading, the properties of composite materials that are anisotropic is not necessarily similar under different types of loadings. The account of combined loading is specifically more critical for woven composites, resulting from the geometrical and mechanical interactions between warp and weft yarns. In general, in order to design any composite structure (woven or non-woven) with the highest performance reliability, it would be desired to characterize the mechanical behavior of the material under several combined loadings, rather than individual deformation modes. One common type of combined loadings is biaxial loading in which primarily a test specimen is subjected to equi-biaxial tension. However, providing facilities to apply such multi-axial tests is sometimes expensive and challenging. Moreover, creating a homogenous deformation in the zone of interest in biaxial specimens, normally far away from the loading jig, is crucial so as to obtain reliable characterization results. Furthermore, stress concentration in the specimen resulting from the sample shape in biaxial tests makes their analysis more complicated. In other words, a correct calculation of effective stress and strain either by analytical or numerical approaches should be considered next to the experimental testing. Currently, there is limited standard for biaxial testing of composites [43], whereas there are several standards for testing individual deformation modes, such as ASTM D3039 for the uniaxial tensile testing of composite materials. The biaxial testing of dry woven fabric materials using customized fixtures has substantiated the presence of severe coupling effects between warp and weft directions under different deformation modes [19]. In another recent study regarding a state-of-the-art combined biaxial-shear testing of dry carbon fabrics, Nosrat-Nazemi et al. conducted shear as well as biaxial tension-shear experiments [20]. Their results clearly demonstrated that there is another nonlinear coupling between the global shear behavior of the woven fabric specimens and the pre-tension applied to the samples.

The biaxial behavior of coated fabric materials has also shown that these materials behave substantially different by changing the ratio of applied stress in the warp direction to the applied stress in the weft direction. One of the first studies in this area, performed by Reinhardt, showed that the stiffness and ultimate strain of coated fabrics changes with different loading ratios between warp and weft [21]. In another study of coated fabric composites, Galliot and Luchsinger presented a simple model for non-linear unequi-biaxial tensile behavior of PVC-coated polyester fabrics based on experiments. In their model, the Young's modulus of different directions changed by changing the loading ratio [22]. Actually, this change resulted from the significant effect of interaction between warps and wefts. A linear relation between the Young's modulus and the loading ratio was also found in their investigation experimentally.

By refereeing to the above biaxial tests on dry and coated woven fabrics, the effect of interactions between warp and weft yarns under different modes has been well evidenced [19–22]. However, the influence of yarns' interaction in fully consolidated woven composites has not been explored in full. In three investigations [44–46], Welsh et al. studied the biaxial behavior of IM7-977-2 carbon-epoxy and E-glass vinyl plain weave composite laminates. Their results showed the existence of biaxial strengthening effect. However, the researchers of World Wide Failure Exercise recommended more experimental studies, as well as more attempts to advance the generalized set-ups of biaxial tests, on consolidated woven composites because of the scarcity of information in this area [3]. Regarding analytical studies on combined loading of consolidated textile composites, Welsh and co-workers [44–46] endeavored to predict the behavior of fabric composites using a multi-continuum theory (MCT). However, there was not sufficient agreement between the experimental and MCT results. In another study, Key et al. utilized multi-continuum theory in which warp and weft yarns as well as the matrix were considered as three model constituents [47]. Comparison between the analytical results and the experimental data obtained by Welsh et al. showed more compatibility because of employing a progressive damage model based on a continuous material property degradation state.

In conclusion, although the interweaved fiber architectures of woven composites bring assets such as out-of-plane impact resistance, ease of molding processes, and better resistance to damage growth, such complex material structures also cause difficulties for their analyses; three of which are in-plane as well as out-of-plane waviness and coupling effects between warp and weft yarns. In the modeling works reviewed above, researchers successfully took the advantage of some simplifications and assumptions in order to consider some of the aforementioned complexities. However, there is no explicit and practical damage model developed for woven composites yet, as also highlighted in the World Wide Failure Exercise [3]. It is believed that as the first step toward such comprehensive models under different deformation modes and different loading regimes (including loading–unloading and viscoelasticity), the underlying local damage mechanisms and their progression should be further explored under *individual* and *combined* failure modes via advanced experimental/numerical studies to understand their effects on the global stress-strain behavior of woven composites. Some preliminary results in this direction will be presented in Section 3.

### 2.2. Damage models for non-woven fabric composites

Several efforts have been put into research to accurately predict the mechanical behavior of non-woven fabric composites. As an example of such predictions, Cox assumed the paper material is composed of perfectly homogeneous plane of non-interactive long straight fibers which are oriented randomly. The material elastic modulus was calculated for small deformation regimes [48]. Applying an orthotropic model, Backer and Petterson investigated the tensile behavior of non-woven composites [49]. In an orthotropic model, stiffness coefficients in an arbitrary direction for small deformation can be estimated by knowing the stiffness constants in two main (principal) directions. There was a fair compatibility between the obtained initial elastic modulus from analytical and experimental analyses. However, non-woven composites can be inherently random anisotropic materials due to the non-uniformity of oriented fibers. Non-uniform distribution of fibers was first taken into account in the studies [50–51]. In these works, the authors presumed that a non-woven fabric specimen is made of many layers of fibers with various orientations bonded to each other. However, fiber re-orientation was ignored on account of the bonding between fiber layers. Demirci et al. discussed the anisotropy of non-woven fabrics through continuum mechanics, based on the randomness of fiber orientation [52]. Utilizing image processing of data acquired by Scanning Electron Microscopy (SEM) and X-ray tomography, orientation distribution function (ODF) was measured as a representative of orientation randomness of fibers. Then, using the Fourier series, some parameters were defined to show the level of orthotropy. The analytical results which had good agreement with experimental results demonstrated a significant direction-dependence of nonwovens. In one of the other latest studies employing continuum mechanics [53], Ridruejo et al. presented a constitutive model for in-plane behavior of non-woven felts that included three parts: fibrous network, fibers, and damage. For modeling the fibers network, they followed Cox's model in which fibers do not have any interaction with each other. However, fiber orientation in large deformation was considered in the model. The damage of bonds and fibers were incorporated in the study in a phenomenological way. However, this method was not able to give a profound insight into the micro-level mechanical behavior of these materials which have more complex fibrous architecture than woven and UD composites. In other words, most of reported analytical works cannot precisely consider actual effects such as fibers reorientation, fibers sliding, and progressive damage propagation.

In order to arrive at a better understanding of the mechanical behavior of non-woven fabrics, representative unit cells (RUCs) can be employed based on numerical homogenization. The first study of this kind focusing on the micromechanics of non-woven composites was carried out by Petterson [54]. Straight fibers were modeled based on a specific statistical distribution within a unit cell. Another assumption in the simulation was a rigid bond between fibers. Thereafter, Hearle and Stevenson attempted to improve Peterson' fibrous network model by taking fiber curls into account [55]. The results demonstrated that fiber curl has a significant effect on the initial modulus of non-woven fabrics. The previous models were valid for in plane deformations. Narter et al. presented a 3D micro-mechanical model for prediction of elastic constants of non-woven composites, taking into account fiber elastic modulus, fiber linear density, and fabric bulk density [56]. Another extension of Petterson's work, considering the time-dependence behavior of felt composites, was performed by Kothari and Patel [57]. They investigated the creeping behavior of non-woven fabrics by considering the viscoelastic behavior of fibers. In another work, Silberstein et al. presented a micromechanical model for non-woven polymer fabrics that was able to implement an elasto-plastic behavior of fibers [58]. The obtained initial modulus and yield stress were based on fiber properties, network geometry, and network density. However, as similarly discussed for the RVE micromechanics of woven fabrics (section 2.1.1), this approach has several disadvantages, the main of which being lack of damage localization. Namely, this technique states that when damage initiates in a representative unit cell, it arises in the whole sample. However, this behavior could be contrasting with what is observed in reality where failure begins in a point of material medium, and then propagates to other points of the sample. Moreover, the RUC procedure may not able to fully predict damage propagation of non-woven felts due to the presence of more randomness than, e.g., woven composites. Furthermore, on account of existence of voids, various fiber concentrations, and non-uniform fiber orientations at different points of a non-woven fabric, the homogenization rule may not be fully valid. In other words, the micro behavior of representative volume cells should be very cautiously extended to the macro behavior of non-woven felts. Therefore, some researchers decided to sacrifice computational time for accomplishing more reliable results by modeling the entire specimen at the micro/meso level instead of a single unit cell. Although this method is computationally expensive and may not be directly applied to large scale structures, small laboratory-scale specimens can be modeled and compared to experiments. In this type of modeling, however, simulation of bonding between fibers is controversial. In some studies, rigid contacts were defined between fibers. The first group of analyses that implemented this assumption was performed by Britton et al. [59–61]. Although they considered rigid contacts in bonds, they took into account bonding breakage. For the determination of bonding failure, they assumed when the force of a fiber exceeds a certain value, the fiber is debonded from the bond point. In another study, Wu and Dzenis considered the elastic behavior of planar fiber networks numerically [62]. In their simulations, slippage of fibers on each other and their angular displacement were overlooked. Constitutive equation was found based on the average of dissipated energy in each fiber. The numerical results were fairly comparable with analytical predictions. To make use of more advanced fiber contact models, Grindstaff and Hansen used springs to model bonds between fibers [63]. In order to determine the stiffness of springs, tensile tests were carried out on one single bond. One of the other advanced contact simulations was performed by Ridruejo et al. [64]. They simulated the behavior of glass fiber non-woven fabrics by explicitly introducing the fiber bundles using a random distribution. The implemented mechanical behavior and geometrical parameters of fibers were measured by removing a single fiber from the fabric and applying tensile test on it. In order to model a realistic contact, tiebreak contact was utilized in which fibers were jointed at their crossovers until bonding failure occurs. Although fibers do not move together after debonding, there was a pre-defined friction between them due to the use of this type of contact, which brought another capability of the model to consider fibers sliding. Experimental results of that study demonstrated that the main and first induced failure mode in non-woven fabrics under tension is bonding failure which propagates and creates a wide band. There was a good agreement between numerical and experimental results. Farukh et al. simulated thermally bonded nonwovens with a new insight into the bonding issue [65]. It has been reported that during the manufacturing process, high temperature and pressure at bond points can cause changes in molecular arrangement of fibers [66]. Additionally, stress concentration exists in fiber crossover points of nonwovens, similar to woven composites. As a result, the mechanical behavior of fibers in a fibrous network is different between an original fiber before the fabrication process and a fiber removed from the fabricated fabric sample. Hence, they extracted a fiber from the fabric sample in a way that the fiber was jointed to bonds at both ends. Their tensile tests showed that the ultimate strength and strain of fibers within fabrics are less, in comparison with those of unprocessed fibers. The numerical simulation was able to predict the general behavior of non-woven felts under tension with a reasonable accuracy.

## 3. Recent progress on further understanding of the damage behavior of woven composites

According to the aforementioned issues (section 2.1) for accurate damage modeling of woven composites, in light of their interwoven architectures—the main reason of superb behavior of these composites—there are several intrinsic distinctions that should be made between the mechanical behavior, particularly failure mechanism of long-fiber woven and UD composites. Before developing further enhanced and realistic damage models for woven composites, it is believed that the underlying sources of complexity need to be explored under various loading types. Among these, the impact of inherent in-plane waviness—misalignment—and out-of-plane waviness in yarns—crimping—on the damage mechanism of woven composites under tensile and bending modes has been recently investigated by the authors [67, 68], and is briefly reviewed here.

### 3.1. The in-plane waviness effect

A detailed experimental investigation was carried out into the mechanical behavior of a consolidated polypropylene/glass twill lamina under uniaxial tensile loading in warp and weft directions. Digital image correlation (DIC) and microscopy were employed in order to find the effect of in-plane waviness of fibers on the material response at each stage of tension. All the tests were performed based on ASTM D3039. Three test repeats were performed for each direction (warp and weft) in order to ensure the repetitiveness of results, as also confirmed by related statistical tests [67]. Figure 5 illustrates the presence of in-plane waviness in the studied specimens. In practice, in addition to out-of-plane waviness through the thickness of a woven specimen due to the interlacement of yarns in weaving process, the warp yarns of consolidated specimens through vacuum infusion technique were wavy in the plane of lamina, whereas the weft yarns were almost straight; this clearly indicated that the manufacturing/lamination process itself can add additional complexities to the mechanical behavior of woven composite structures.

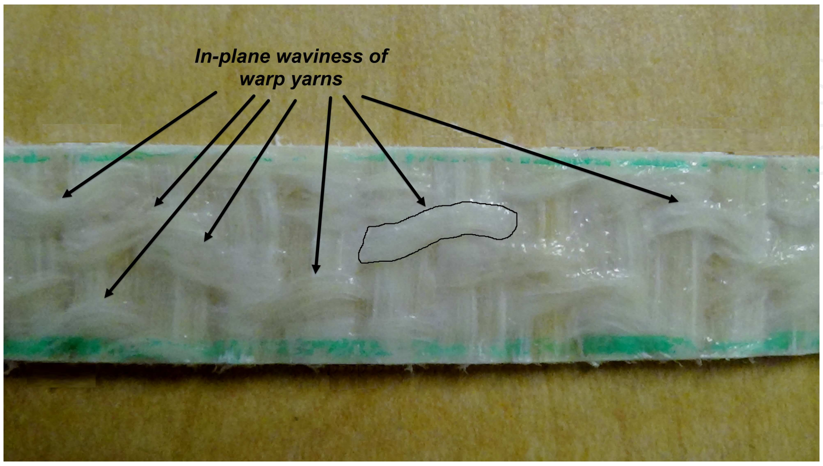


**Figure 5.** Example of in-plane waviness of warp yarns in a woven cured composite (notice that the weft yarns are nearly straight in the plane of fabric) [67].

Figure 6 shows the example of stress-strain behavior of the twill fabric samples obtained in the warp and weft directions. As depicted, the tensile behavior in the weft direction of the samples is almost linear up to the final failure with a sudden drop, which is analogous to that of most UD composites. On the other hand, the specimen responded non-linearly under the warp direction loading and then encountered failure in multiple steps with small falls at each. The results of DIC and microscopy pointed out that the main reason of such differences is the existence of in-plane waviness in the warp yarns. In fact, when the twill composite specimen was subjected to tension in the warp direction, the warp yarns which inherently had more in-plane waviness than weft (fill) yarns due to weaving process, moved similar to 'snakes sliding' on a ground of matrix, hence changing the global stiffness of the sample. Although matrix cracking followed by fiber breakage arose in the samples of both directions, as illustrated in Figure 7, performing analytical and statistical analyses on the obtained results from DIC, a high resolution stereotype microscope, and visual observations of tested samples demonstrated that the reason of matrix cracking is totally different between the warp and weft directions. Namely, the matrix experienced shear failure in warp direction whereas matrix tensile failure occurred in the weft direction. This difference in failure mode of matrix causes a sooner matrix crack initiation in specimens under tension in the warp direction. Not only does in-plane waviness affect the local damage behavior of woven composites in different directions, but also it can change the effective (global) mechanical properties such as Young's modulus, ultimate strength, and ultimate strain.

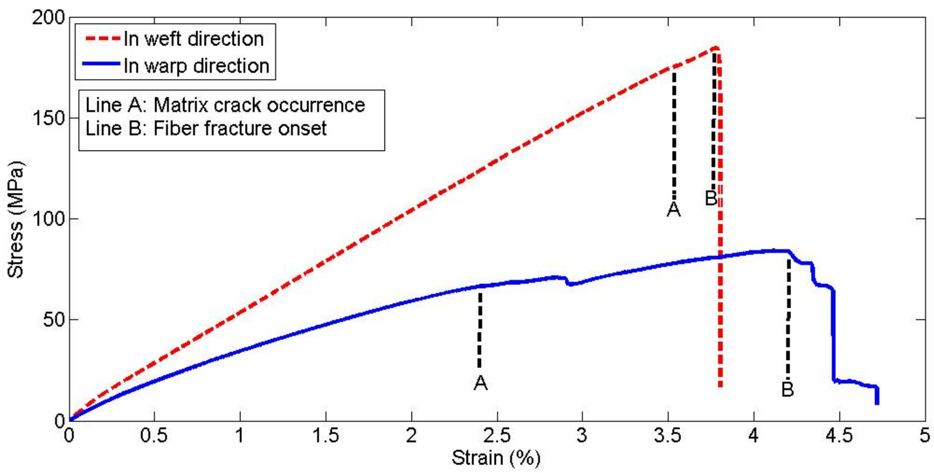


**Figure 6.** A comparison between the stress-strain behavior of the cured PP/glass twill lamina in the warp and weft directions: (A) Matrix cracking initiation, (B) Fiber fracture onset [67].

### 3.2. The out-of-plane waviness effect

In-plane waviness discussed in the previous section could mainly affect the tensile behavior of woven composites, rather than their bending behavior. On the other hand, undulation is the cause of less stiffness of woven composites in comparison with comparable UD composites with the same fiber/matrix constituents. Expectedly, fiber crimping should make the behavior

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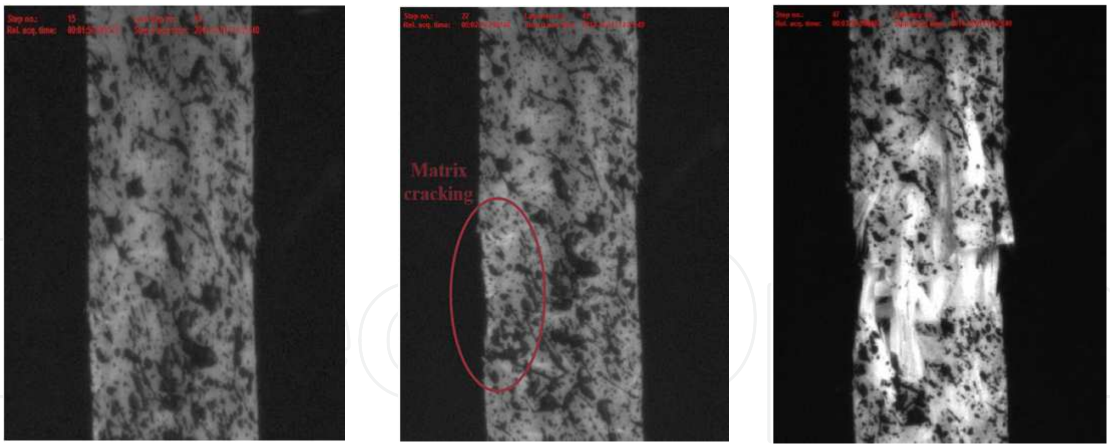


(a) Before damage initiation (b) Matrix cracking onset (c) Final failure (fiber fracture)

**Figure 7.** Different steps of mechanical behavior of twill composite specimen under warp tension (the white region in the red ellipse of panel (b) that does not exist in panel (a) points to the matrix cracking in macro level) [67].

of woven composites quite distinct from UDs under bending. To divulge this, the damage mechanism of oven-vacuum bagged twill glass/PP composite specimens under three-point bending was investigated [68]. The specimens were comprised of six twill layers with 6.18 mm of total thickness. Other dimensions of the specimens and deformation rate of loading were selected based on ASTM D7264. DIC was exploited to precisely observe the failure mechanisms of the woven composite samples step-by-step. The effect of surface quality was also examined in order to take into account the effect of the manufacturing process itself. In fact, due to the existence of crimping in woven composites, each studied specimen had two different surface conditions on its sides; one of which was almost flat as it was adjacent to the metallic mould during vacuum process. As a consequence, it was under more pressure, causing the undulation of the layer to fade. The other surface (open side) that was inherently not subject to the same processing pressure was wavy, with an average amplitude of 0.4 mm. Figure 8 demonstrates these two surfaces. As a result, two groups of samples were considered in the subsequent statistical analysis of the study. Namely, the specimens were subjected to loading in two conditions in which either the smooth or the curvy surface had direct contact with the loading nose.



(a) Bottom view (smooth surface) (b) Upper view (rough/wavy surface) (c) Side view (showing both surfaces at the same time)

**Figure 8.** Different surfaces of an open-molded (oven vacuum bagged) twill specimen [68].

Typical bending responses of samples under the two surface conditions are presented in Figure 9. Although for both loaded surfaces, the bending response is linear until the first failure mode —fiber compression failure, significant differences can be observed between the two curves in Figure 9, proving the effect of surface quality (manufacturing) and eventually out-of-plane waviness of fibers on the bending behavior of woven composites.

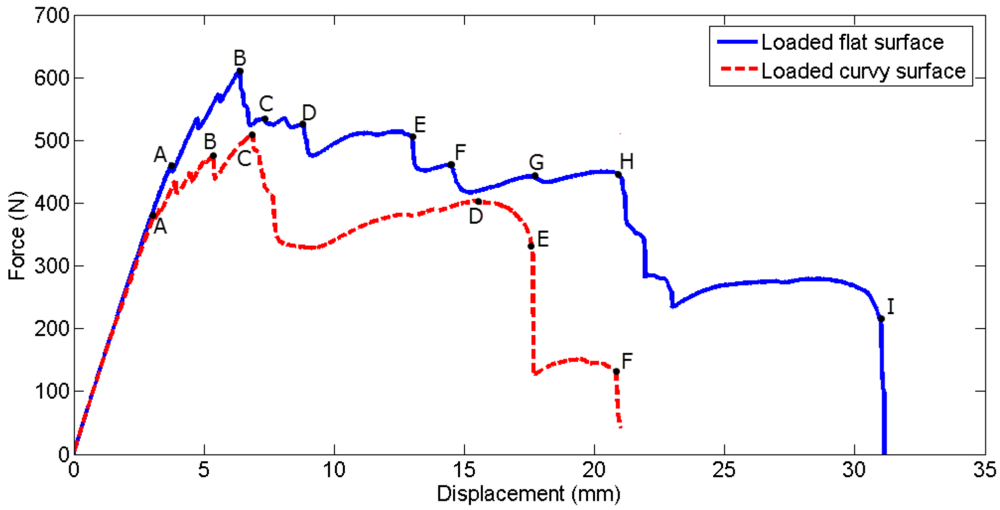


**Figure 9.** Comparison between the bending responses of two woven composite specimens with different loaded surfaces. For *flat surface loaded sample:* Point A: Initiation of fiber micro buckling in the first (top) layer, Point B: Completion of failure in the first layer, Point F: complete compression failure in the second layer, Point C and G: Delamination occurrence, Point H: Onset of fiber tensile failure in the lowest layer ($6_{th}$), Point I: Complete fiber breakage in $5_{th}$ layer. For *curvy surface loaded sample*: Point A: Initiation of fiber micro buckling in the first (top) layer, Point B: Completion of failure in the first layer, Point C: Complete compression failure in the second layer, Point D: Nucleation of fiber breakage in the lowest layer, Point E: Complete failure in the lowest layer, Point F: Complete fiber tensile failure in the $5_{th}$ layer [68].

Figure 10 further investigates the failure mechanisms of specimens in each loading condition. The DIC results informed that crimping can cause fiber compression failure not to occur exactly in the middle of the beam specimen where the applied (global) bending moment is maximum. In fact, due to the crimping, yarns in woven composites are comparable to sinusoidal beams with various amplitudes of waviness over their longitudinal axis, as illustrated in Figure 11. The higher the amplitude at a point, the less the buckling force of that location of yarn, and hence, a higher chance of failure initiation at that point. Consequently, the location in which fiber compression failure begins depends not only on the amount of applied bending moment, but also on the crimping amplitude of that point—which in effect changes the critical force of micro-buckling. However, delamination, the most common disadvantage of UD composites under bending due to the significant mismatch between layers of UD laminates, occurred only when the flat surface of the woven samples was under loading. However, concurrently taken photos by DIC and the force-displacement curves obtained by Instron machine divulged that delamination is not so influential to substantially drop the global force, point C and G in "loaded flat surface" curve as shown in Figure 9. The given interpretation for this observation may be that the debonded area is restricted between cells in woven composites, as shown in Figure 12(a). Hence, it cannot grow through the whole interface between the two layers, while the delamination area is much larger in UDs because it can propagate substantially [41].

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Supporting this hypothesis, the actual micrograph in Figure 12(b) showed that matrix cracking has in the red regions of Figure 12 (a) where there is no fibers to resist the loading. These matrix cracks then resulted in debonding between the two layers. It is to note that along with the effect of out-of-plane waviness on the damage mechanism of woven composites, this type of waviness can affect the bending material parameters such as maximum force, ultimate deflection, and absorbed energy. For instance, the ultimate deflection was different by 37% between the two samples as seen in Figure 9.

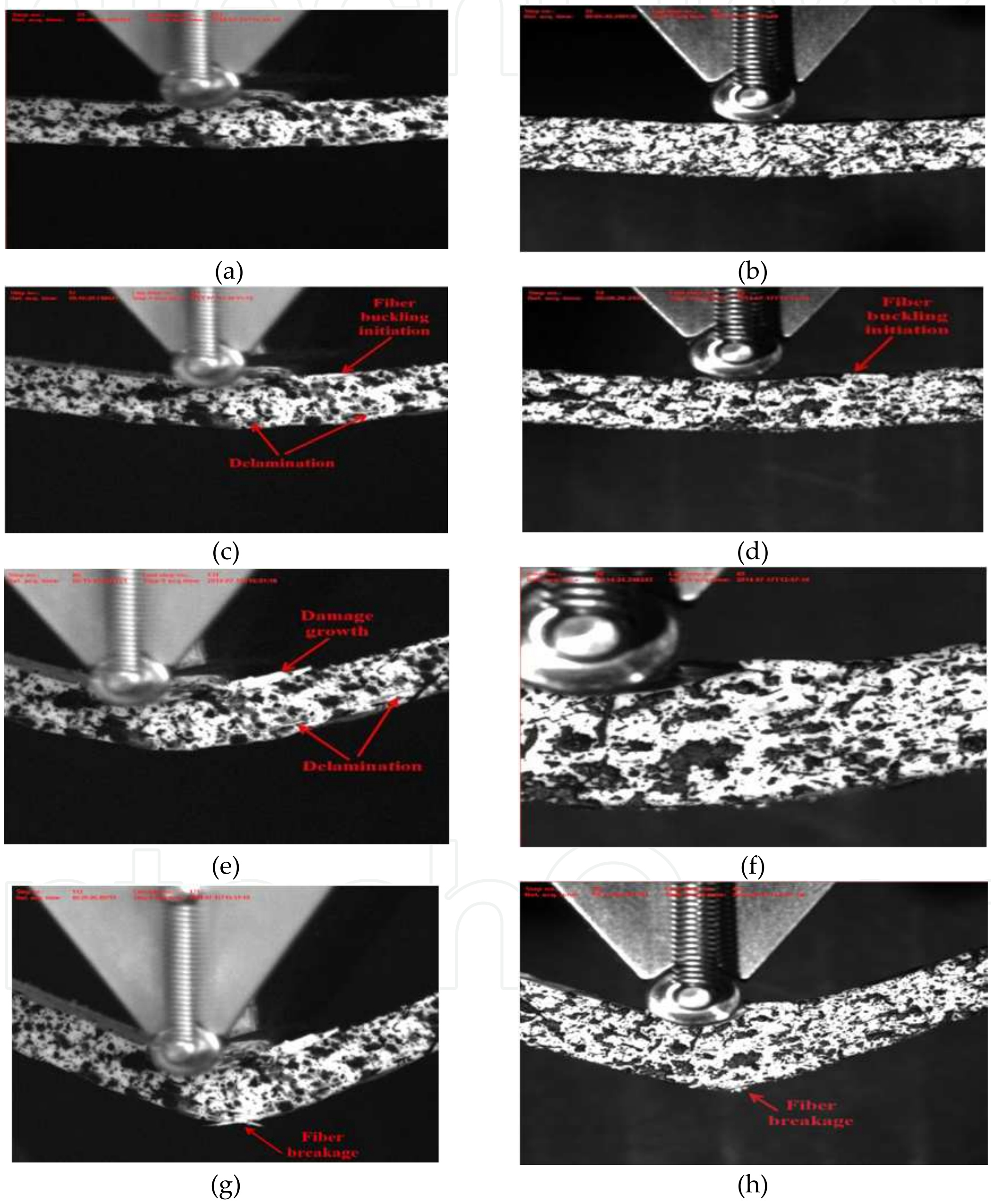



**Figure 10.** Damage mechanisms in two woven three-point bending specimens; left photos (a), (c), (e), and (g) correspond to the specimen loaded on a flat surface; right images (b), (d), (f), and (h) are for the specimen loaded on a curvy surface. (a) and (b): Specimens before any damage onset; (c) and (d): Initiation of fiber micro buckling; (e) and (f): Propagation of fiber buckling; (g) and (h): Fiber breakage initiation [68].

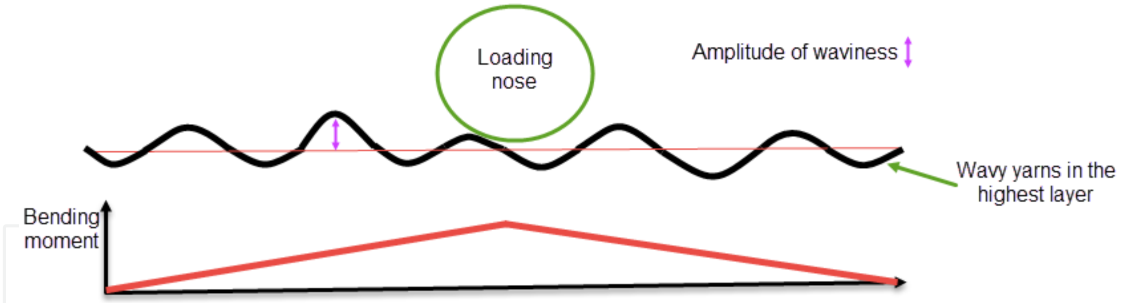
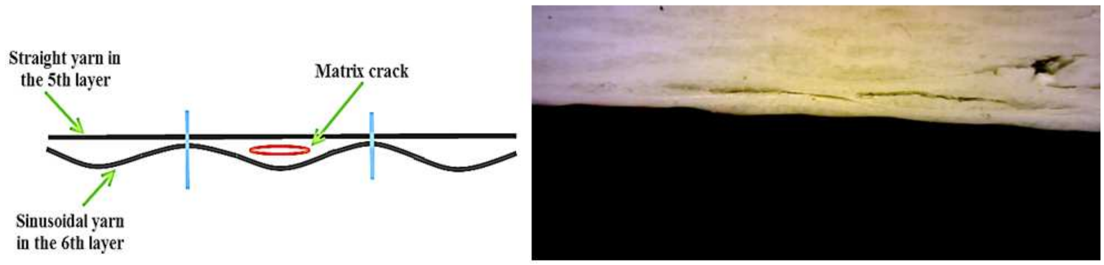



**Figure 11.** Schematic of varying bending moment and waviness amplitude in different locations of a yarn, especially in the open-side of the molded specimen (i.e., the highest layer of laminate).




(a) (b)

**Figure 12.** Restricted matrix crack in the woven composite specimen. (a) Schematic diagram; (b) Actual micro-image of cracks from the sample under three-point bending [68].

## 4. Conclusion and anticipated future developments

Based on the conducted review, the interlaced fiber architecture of woven composites, the main reason of their superb behavior, causes a series of complexities such as in-plane as well as out-of-plane misalignment effect in the laminated parts, along with a coupling between warp and weft yarns, all of which having a different effect under different deformation modes. As an example, recent experimental results show that not only the in-plane waviness inherited from the waving process is one of the reasons of non-linearity in uniaxial tensile behavior of woven composites, but it also leads to a significant unbalance in the damage tolerance measure in warp and weft directions. In effect, material properties such as Young's modulus, ultimate strength, and ultimate strain of the two principal directions of woven laminates should be expected to be statistically different in the presence of processing-induced in-plane waviness, despite the fact that as-received fabric preforms are often assumed balanced. In addition, evidence in the literature demonstrates that out-of-plane waviness can yield unusual failure modes in open-molded woven composites under three-point bending mode, similar to the propagation of "Plate Tectonics" in Geology. So dominant is the effect of yarn crimping that a change in the loaded surface of a sample can lead to a significant decrease in the bending resistance of the open-molded woven laminates. Moreover, it was observed that in converse with UD composites, in which interlaminar failure grows instantly, delamination can be well confined between the cells of a weave architecture and not extended to the entire sample, hence inducing higher damage tolerance.

Owing to the aforementioned complexities in the response of woven fabrics, earlier micro, meso, and macro level damage models of UDs may not be fully compatible to predict the behavior of woven structures under various loading regimes, while fulfilling high accuracy and minimum computational cost. To meet the two latter practical requirements, the most appropriate way to analyze woven composites and to predict their damage is believed to be the phenomenological approach, along with required experimental analyses. Currently, there is no comprehensive experimental study revealing the effect of woven architecture of fibers in a multitude of deformation modes, classifying the dominant failure modes specifically to these composites, and eventually presenting an explicit, short, and easy-to-implement phenomenological model for the damage nucleation stage and finally growth. Moreover, different stress-strain behaviors of textile composites with non-linear functions have been employed in the previous macro-level research investigations, while there have been no sufficient mirco/meso level evidence on the roots of this non-linearity. As reviewed in this chapter, the determination of the sources behind material non-linearity is crucial to propose accurate damage models. Furthermore, with the exception of a few recent works, past researches have not paid close attention to combined loading effects—which are very likely in practical applications—on the behavior of woven composites. Recent experimental works reveal that the interaction between warp and weft yarns has a significant effect on both dry and coated fabrics under combined loadings; however, to the best of authors' knowledge, no detailed study of this kind has been reported for consolidated laminates. In addition, the characterization of loading-unloading behavior of woven composites in quasi-static and high strain rate regimes (e.g., for application in inflatable fabric tube, or impact design of structures), particularly after arising some first damage, have not received sufficient consideration.

Regarding the analysis of non-woven fabrics, in addition to the aforementioned complexities in woven composites, more complexities such as non-uniform fiber architecture, fiber sliding, and complex bonding behavior between fibers need to be addressed. As a consequence, the analysis of non-woven felts is deemed more complicated than woven composites, despite several general similarities seen in damage modeling approaches taken for both types of fabric materials.

Finally, it is noticed that statistical analysis has taken little part in the past characterization efforts on fabric reinforced composites. This is despite the fact that uncertainties underlying the soft reinforcing materials in the dry form [69], along with process-induced uncertainties and risk during matrix curing/manufacturing stages, may have an enormous effect on the variation of parameters needed for damage modeling. Subsequently, the application of hypothesis testing and black-box optimization methods in the field of damage modeling of composites is believed to be vital in future studies to ensure the reliability and applicability of the identified models.

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## References

[1] Dixit A, Mali HS. Modeling techniques for predicting the mechanical properties of woven-fabric textile composites: A review. Mechanics of Composite Materials. 2013;49(1):1-20.

[2] Russell S. Handbook of Nonwovens. Woodhead Publishing. 2006.

[3] Soden P, Kaddour A, Hinton M. Recommendations for designers and researchers resulting from the world-wide failure exercise. Composites Science and Technology. 2004;64(3):589-604.

[4] Blackketter D, Walrath D, Hansen A. Modeling damage in a plain weave fabric-reinforced composite material. Composite Technology and Research. 1993;15(2):136-142.

[5] Tang X, Whitcomb JD. Progressive failure behaviors of 2D woven composites. Composite Materials. 2003;37(14):1239-1259.

[6] Jia X, Xia Z, Gu B. Micro/meso-scale damage analysis of three-dimensional orthogonal woven composites based on sub-repeating unit cells. The Journal of Strain Analysis for Engineering Design. 2012;47(5):313-328.

[7] Jia X, Xia Z, Gu B. Numerical analyses of 3D orthogonal woven composite under three-point bending from multi-scale microstructure approach. Computational Materials Science. 2013;79:468-477.

[8] Chandekar GS, Kelkar AD. Experimental and numerical investigations of textile hybrid composites subjected to low velocity impact loadings. The Scientific World Journal. 2014.

[9] Ishikawa T, Chou T. Stiffness and strength behaviour of woven fabric composites. Materials Science. 1982;17(11):3211-3220.

[10] Ganesh V, Naik N. Failure behavior of plain weave fabric laminates under on-axis uniaxial tensile loading: I—laminate geometry. Composite Materials. 1996;30(16): 1748-1778.

[11] Naik N, Ganesh V. Failure behavior of plain weave fabric laminates under on-axis uniaxial tensile loading: I—analytical predictions. Composite Materials. 1996;30(16): 1779-1822.

[12] Tabiei A, Song G, Jiang Y. Strength simulation of woven fabric composite materials with material nonlinearity using micromechanics based model. Thermoplastic Composite Materials. 2003;16(1):5-20.

[13] Li J, Zhao M, Gao X, Wan X, Zhou J. Modeling the stiffness, strength, and progressive failure behavior of woven fabric-reinforced composites. Composite Materials. 2013;0021998313477171.

[14] Manual LKU. Version R7. 0. Livermore Software Technology Corporation 2013.

[15] Feng Z, Allen HG, Moy SS. Study of stress concentrations in woven composites. Reinforced Plastic Composites. 1999;18(3):198-214.

[16] Tsai SW, Wu EM. A general theory of strength for anisotropic materials. Composite Materials. 1971;5(1):58-80.

[17] Chang F, Chang K. A progressive damage model for laminated composites containing stress concentrations. Composite Materials. 1987;21(9):834-855.

[18] Hashin Z. Failure criteria for unidirectional fiber composites. Applied Mechanics 1980;47(2):329-334.

[19] Buet-Gautier K, Boisse P. Experimental analysis and modeling of biaxial mechanical behavior of woven composite reinforcements. Experimental Mechanics. 2001;41(3):260-269.

[20] Nosrat-Nezami F, Gereke T, Eberdt C, Cherif C. Characterisation of the shear–tension coupling of carbon-fibre fabric under controlled membrane tensions for precise simulative predictions of industrial preforming processes. Composites Part A: Applied Science and Manufacturing. 2014;67:131-139.

[21] Reinhardt HW. On the biaxial testing and strength of coated fabrics. Experimental Mechanics. 1976;16(2):71-74.

[22] Galliot C, Luchsinger R. A simple model describing the non-linear biaxial tensile behaviour of PVC-coated polyester fabrics for use in finite element analysis. Composite Structures. 2009;90(4):438-447.

[23] Hufner DR, Accorsi ML. A progressive failure theory for woven polymer-based composites subjected to dynamic loading. Composite Structures. 2009;89(2):177-185.

[24] Hill R. A theory of the yielding and plastic flow of anisotropic metals. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences. 1948:281-297.

[25] Vaziri R, Olson M, Anderson D. A plasticity-based constitutive model for fibre-reinforced composite laminates. Composite Materials. 1991;25(5):512-535.

[26] Strong A. Brent. Fundamentals of composites manufacturing: Materials, methods and applications. Society of Manufacturing engineers. 2008.

[27] Kachanov L. Time of the rupture process under creep conditions. Isv. Akad. Nauk. SSR. Otd Tekh. Nauk. 1958;8:26-31.

[28] Frantziskonis G. Distributed damage in composites, theory and verification. Composite structures. 1988;10(2):165-184.

[29] Feng Z, Allen HG, Moy SS. Theoretical and experimental investigation of progressive failure of woven composite panels. Composite Materials. 1999;33(11):1030-1047.

[30] Ladeveze P, LeDantec E. Damage modelling of the elementary ply for laminated composites. Composites Science and Technology. 1992;43(3):257-267.

[31] Johnson AF. Modelling fabric reinforced composites under impact loads. Composites Part A: Applied Science and Manufacturing. 2001;32(9):1197-1206.

[32] Hochard C, Aubourg P, Charles J. Modelling of the mechanical behaviour of woven-fabric CFRP laminates up to failure. Composites Science and Technology. 2001;61(2): 221-230.

[33] Iannucci L, Dechaene R, Willows M, Degrieck J. A failure model for the analysis of thin woven glass composite structures under impact loadings. Computers and Structures. 2001;79(8):785-799.

[34] Iannucci L. Progressive failure modelling of woven carbon composite under impact. Impact Engineering. 2006;32(6):1013-1043.

[35] Iannucci L, Willows M. An energy based damage mechanics approach to modelling impact onto woven composite materials—Part I: Numerical models. Composites Part A: Applied Science and Manufacturing. 2006;37(11):2041-2056.

[36] Cousigné O, Moncayo D, Coutellier D, Camanho P, Naceur H. Numerical modeling of nonlinearity, plasticity and damage in CFRP-woven composites for crash simulations. Composite Structures. 2014;115:75-88.

[37] Blacklock J, Richard R. Finite element analysis of inelastic structures. AIAA. 1969;7(3):432-438.

[38] Brown K, Brooks R, Warrior N, Numerical simulation of damage in thermoplastic composite materials. In: Proceedings of the 5th European LS-DYNA Users Conference; May 2005; Birmingham, UK, p. 25-26.

[39] Song Z, Wang Z, Ma H, Xuan H. Mechanical behavior and failure mode of woven carbon/epoxy laminate composites under dynamic compressive loading. Composites Part B: Engineering. 2014;60:531-536.

[40] Evci C, Gülgeç M. An experimental investigation on the impact response of composite materials. Impact Engineering. 2012;43:40-51.

[41] Kim J, Sham M. Impact and delamination failure of woven-fabric composites. Composites Science and Technology. 2000;60(5):745-761.

http://dx.doi.org/10.5772/61511

[42] Mallikarachchi H, Pellegrino S. Failure criterion for two-ply plain-weave CFRP laminates. Composite Materials. 2013;47(11):1357-1375.

[43] Escárpita DAA, Cárdenas D, Elizalde H, Probst O, Ramirez R. Biaxial Tensile Strength Characterization of Textile Composite Materials. INTECH Open Access Publisher, 2012. P. 83-106.

[44] Welsh JS, Mayes JS, Biskner AC. 2-D biaxial testing and failure predictions of IM7/977-2 carbon/epoxy quasi-isotropic laminates. Composite Structures. 2006;75(1): 60-66.

[45] Welsh JS, Mayes JS, Key CT, McLaughlin RN. Comparison of MCT failure prediction techniques and experimental verification for biaxially loaded glass fabric-reinforced composite laminates. Composite Materials. 2004;38(24):2165-2181.

[46] Welsh JS, Adams DF. An experimental investigation of the biaxial strength of IM6/3501-6 carbon/epoxy cross-ply laminates using cruciform specimens. Composites Part A: Applied Science and Manufacturing. 2002;33(6):829-839.

[47] Key CT, Schumacher SC, Hansen AC. Progressive failure modeling of woven fabric composite materials using multicontinuum theory. Composites Part B: Engineering. 2007;38(2):247-257.

[48] Cox HL. The elasticity and strength of paper and other fibrous materials. British Journal of Applied Physics. 1952;3(3):72.

[49] Backer S, Petterson DR. Some principles of nonwoven fabrics1. Textile Research Journal. 1960;30(9):704-711.

[50] Bais-Singh S, Goswami BC. Theoretical determination of the mechanical response of spun-bonded nonwovens. Journal of the Textile Institute. 1995;86(2):271-288.

[51] Liao T, Adanur S, Drean J. Predicting the mechanical properties of nonwoven geotextiles with the finite element method. Textile Research. 1997;67(10):753-760.

[52] Demirci E, Acar M, Pourdeyhimi B, Silberschmidt VV. Computation of mechanical anisotropy in thermally bonded bicomponent fibre nonwovens. Computational Materials Science. 2012;52(1):157-163.

[53] Ridruejo A, González C, LLorca J. A constitutive model for the in-plane mechanical behavior of nonwoven fabrics. Solids Structures. 2012;49(17):2215-2229.

[54] Petterson DR. On the Mechanics of Nonwoven Fabrics [PhD Thesis]. Massachusetts Institute of Technology; 1959.

[55] Hearle J, Stevenson P. Studies in Nonwoven Fabrics Part IV: Prediction of Tensile Properties1. Textile Research. 1964;34(3):181-191.

[56] Narter MA, Batra SK, Buchanan DR, Micromechanics of three-dimensional fibre-webs: Constitutive equations. In: Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences; 1999. p. 3543-3563.

[57] Kothari V, Patel P. Theoretical model for predicting creep behaviour of nonwoven fabrics. Indian Journal of Fibre and Rextile Research. 2001;26(3):273-279.

[58] Silberstein MN, Pai C, Rutledge GC, Boyce MC. Elastic–plastic behavior of non-woven fibrous mats. Mechanics and Physics of Solids. 2012;60(2):295-318.

[59] Britton PN, Sampson AJ, Elliott C, Graben H, Gettys W. Computer Simulation of the Mechanical Properties of Nonwoven Fabrics Part I: The Method. Text Research. 1983;53(6):363-368.

[60] Britton PN, Sampson AJ, Gettys WE. Computer Simulation of the Mechanical Properties of Nonwoven Fabrics Part II: Bond Breaking. Textile Research. 1984;54(1):1-5.

[61] Britton PN, Sampson AJ, Gettys WE. Computer Simulation of the Mechanical Properties of Nonwoven Fabrics Part III: Fabric Failure. Textile Research. 1984;54(7):425-428.

[62] Wu X, Dzenis YA. Elasticity of planar fiber networks. Applied Physics. 2005;98(9): 093501.

[63] Grindstaff T, Hansen S. Computer model for predicting point-bonded nonwoven fabric strength, Part I. Textile Research. 1986;56(6):383-388.

[64] Ridruejo A, González C, LLorca J. Damage micromechanisms and notch sensitivity of glass-fiber non-woven felts: an experimental and numerical study. Mechanics and Physics of Solids. 2010;58(10):1628-1645.

[65] Farukh F, Demirci E, Sabuncuoglu B, Acar M, Pourdeyhimi B, Silberschmidt VV. Numerical analysis of progressive damage in nonwoven fibrous networks under tension. Solids Structures. 2014;51(9):1670-1685.

[66] Chidambaram A, Davis H, Batra SK. Strength loss in thermally bonded polypropylene fibers. In: INTC 2000 Conference, Dallas, 2000. p. 72-79.

[67] Haghi Kashani M, Milani AS. Understanding the effect of in-plane waviness on damage behavior of cured woven composites. Proceedings of 20$^{th}$ International Conference on Composite Materials; 19-24 July 2015; Copenhagen, Denmark.

[68] Haghi Kashani M, Milani AS. Understanding new damage mechanisms in woven composites: the effect of surface quality. Proceedings of Canadian-International Conference on Composite Materials; 17-20 August 2015; Edmonton, Canada.

[69] Komeili M, Milani AS. Meso-Level Analysis of Uncertainties in Woven Fabrics. VDM Verlag, Berlin, Germany, 2010.