A brief review on the mechanical behavior of nonwoven fabrics

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Abstract
Although nonwovens used in many areas from civil and mechanical engineering to consumer products, research on their mechanical behavior are rather limited in the literature. In this study, a brief overview is presented on the previous research performed to understand the relation between the microstructure and the mechanical behavior of these materials. The research studies are categorized into five sections declining with tensile, creep, bending, dynamic and damage behavior. For each type of behavior, previous research is discussed briefly following by that of the last few years. The review demonstrates that the tensile behavior is understood well whereas there is a limited number of studies in bending and dynamic behavior of nonwoven materials. Future research is expected to be more related on the in-service behavior.

Keywords
Nonwovens, mechanical behavior, recent research

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Introduction
Nonwoven fabrics are a type of advanced materials engineered from a set of irregularly arranged fibers or chopped yarns stiffened by mechanical, chemical or thermal bonding methods.¹ The bonding type, the fiber type and the manufacturing parameters determine the characteristic features of a nonwoven. In contrast to conventional engineering materials, these fabrics have better specific mechanical properties, strength to weight and stiffness to weight ratios.² They can provide innovative and cost-effective solutions for many engineering problems thanks to their versatile properties. For instance, altering the composition of raw materials of fibers or finishing treatment methods can provide high ductility, energy absorption capability, flexibility, absorbency and flame retardancy characteristics for ballistic protection, soil reinforcement, liquid absorbing, and fire insulation applications.³ Furthermore, nonwoven fabrics can also be used as abrasion resistant, anti-static, breathable, dust free, moldable, stiff, and tear resistant materials. Some of the most common products made using these materials are the surgical gowns, disposable nappies, household and personal wipes, wall-coverings, envelopes, roofing products, engineering fabrics, and automotive headliners.

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processes. Preparation and use of dry-laid nonwovens are the largest segment of the nonwoven industry as such nonwoven preparation methods existed since the medieval times.\(^4\) The production of dry-laid nonwovens are expected to expand by 5.3% over the next ten years. Carding, garneting and air-laid pulping are three most used dry-laid web-forming techniques along with mechanical and thermal bonding methods; they originated from textile and paper industries.\(^5\) In wet-laid forming, nonwoven fabrics are manufactured using water. The process is quite capital intensive as it requires excessive amounts of water. Cellulose papers and glass or ceramic based technical papers are the most typical examples of the wet-laid formation. For polymer-laid forming, nonwovens are manufactured using polymer extrusion machines. Hygiene product components, such as backs, leg-cuffs, and coverstocks are the most common examples for polymer-laid nonwovens, manufactured using film type or layered composites.

The fibers that make up the nonwovens can be bonded together with various methods; they are categorized as mechanical, chemical, or thermal bonding. In chemical bonding, bonding agents are used along with spraying, printing, coating or saturation methods to join the fibers into fabrics. The motivation for using bonding agents is to hold fibers together along with enhancing the overall stiffness, softness, and waterproofness of the finished product. Bonding agents can be also applied to the finished product to provide additional functionality to improve their visual appearance, flammability characteristics, and surface roughness.\(^9\)–\(^11\) Wipes, interlinings, home furnishings, and hygiene products are the most common examples of the chemically bonded nonwoven fabrics.

In thermal bonding, dry, polymer, or wet-laid fabrics are stiffened using heating and cooling processes. The application of thermal bonding started in mid 1940s. A process of local heating the fibers to their softening temperature and subsequently cooling them to solidify is applied in order to bond the fibers to each other.\(^12\) Currently, thermally bonded nonwovens can be produced from both thermoplastic fibers (e.g. polyester and polypropylene) and from blends. The rising cost of energy and increased awareness about effects on environment led thermal bonding methods to evolve. Nowadays, high production rates are possible with thermal bonding methods where nearly fully recyclable fiber components can be achieved and finished products can be significantly soft. Moreover, thermal bonding processes require less water and are environmentally friendly, since no latex binders are required, compared to chemical bonding.\(^13\),\(^14\) Diapers, pads, heat, and sound insulation materials and mattresses are the most common examples of thermally bonded nonwovens.

The main method for stiffening fibers in a web is mechanical bonding, with comprising fibers bonded using alternate techniques such as hydro-entangling, stitch-bonding, and needle-punching. In mechanical bonding, some parameters affect significantly the quality of the produced nonwoven, for instance, design of water jet and vacuum systems in hydro-entangling, stitching, and knitting frequencies in stitch-bonding and needle design in needle-punching. Marine hulls, blankets, wall coverings, and Kevlar bullet proof vests are the most prevalent applications of this method.

Although nonwoven materials are much cheaper compared to many advanced materials, such as composites, an initial investment to manufacture can be significant. Therefore, understanding the mechanical behavior of nonwovens gained considerable attention in order to design the manufacturing foundation to produce these materials according to specific requirements. Many computational and experimental studies were performed to understand their mechanical behavior under various types of loading conditions especially in the last decade. In this study, the literature on mechanical behavior of nonwovens is summarized with the focus on the recent works. This brief review covers tensile, creep, bending, dynamic, and damage behaviors behaviors.

**Tensile behavior**

The aim of the early previous studies related to tensile behavior were mainly to understand the effect of production parameters such as bond points, orientation, distribution, fiber curliness, etc., with a relatively simple test. Recently, with the development of advanced simulation and imaging techniques, studies were more concentrated on the correlation of micro-scale images and the mechanical behavior.

The research on tensile behavior of nonwoven fabrics goes back to mid 1960s. A theory based on the resistance to extension of nonwovens was presented using Petterson’s early work on effects of fiber curl.\(^15\) It was shown that fiber curl distribution had a great importance for successful predictions of the stress–strain properties of these fabrics. Then, a qualitative numerical method based on the finite element analysis (FEA) and discrete cell method were introduced to investigate the effects of the curl factor, orientation angle, and web uniformity on lateral contraction characteristics of nonwovens during their tensile deformation.\(^16\) In that study, the new results matched the available experimental and numerical results, and it was found that the three studied factors had a great effect on the final characteristics of nonwoven composites. An analytical theory was introduced to predict the uniaxial stress–strain behavior of spun-bonded nonwovens using the Poisson’s ratios, shearing strains, and orientation of comprising fibers by considering the layered unit cell given in Figure 1 for the analytical theory. It was concluded that the results generated from the analytical theory accurately matched the data from experimental studies. Later, their previous work was extended by utilizing the same unit
cell (see Figure 1) under biaxial tensile loading. It was shown that, stress predictions for the longitudinal direction were consistent with the experimental results. Later, a parametric study was presented\textsuperscript{19} using a modified micromechanical model for thermally bonded nonwoven fabrics to investigate the relationship between fiber orientation angle, fabric strain, and initial loading conditions. In that study, failure criterion of thermally bonded nonwovens was also investigated using pull-out behavior of fibers in the fabrics and it was concluded that as the bond stiffened, lower fiber pull-out stresses occurred.

A study of biaxial tensile behavior of spun bonded nonwoven fabrics was presented in\textsuperscript{20} by considering both experimental and analytical methods. By employing the layer theory in the analytical method, the findings were successfully compared with the experimental results, and it was shown that the fiber orientation angle was crucial in transforming spun bonded nonwovens into general anisotropic structures closely related with geotextile strains (see Figure 2). An analytical method was proposed to predict stiffness parameters of heavy nonwoven geotextiles using layer theory and uniaxial loading conditions\textsuperscript{21}. The results of that study was compared with FEA and it was revealed similar stresses in identical fabrics. Later, the effects of manufacturing parameters on the tensile stiffnesses for thermally bonded nonwoven structures was studied by utilizing an efficient and novel numerical method based on finite element analysis\textsuperscript{22}. It was shown that the use of this newly proposed parametric numerical model greatly reduced a computational time for analysis of the effect of various dimensional parameters on tensile stiffnesses of nonwovens. Uniaxial tensile tests were carried out (at a cross-head speed of 0.8 mm/s) to investigate and compare the in-plane mechanical behavior of nonwoven fabrics with the developed constitutive model\textsuperscript{23}. The effect of temperature change and strain rate on the micromechanisms of deformation and fiber failure was studied for thermally bonded polypropylene nonwoven fabrics\textsuperscript{24} and the influence of these properties on the fiber performance was discussed. Later, microstructural and material characterization of bond points in bi-component fiber nonwovens was investigated using traditional and parametric discrete phase FEA techniques\textsuperscript{25}. Subsequently, the deformation and energy dissipation characteristics were studied with the help of macroscopic mechanical tests, optical microscopy, X-ray tomography and X-ray diffraction.\textsuperscript{26} It was presented that nonwoven fabrics had an extreme energy absorption capacity and strength. The effect of areal weight on mechanical properties and deformation mechanisms of polypropylene nonwoven fabrics was analyzed by performing uniaxial tensile tests together with X-ray studies.\textsuperscript{27} It was shown that nonwoven fabrics with a higher areal weight tended to fail in a rupture-like manner. Effects of fiber orientation and areal density on
the deformation mechanisms of the nonwoven fabrics were studied using a uniaxial tensile testing method and micrograph imaging. It was found that local fiber structure and fiber areal density were very important for the mechanical behavior of nonwovens.

Creep behavior

Many types of nonwovens, such as the ones used in filtration, are exposed to deformation for a significant amount of time. They also work in extreme environmental conditions, such as high temperature and humidity. Thus, their behavior can change significantly in service if they function for a long time. Therefore, the long term creep behavior is quite important for these materials. Investigation of the literature revealed various analytical and numerical theories to explain the creep behavior of nonwovens together with relaxation and constant stress tests. Creep related studies are relatively new as the implantation of some advanced models required some technological developments.

Uniaxial creep and recovery tests were initially employed in. In that study, the well-known Schapery nonlinear analytical constitutive relation, it was concluded that the creep strain of nonwovens could be divided into four parts: instantaneous elastic, instantaneous plastic, visco elastic, and viscoplastic. Anisotropy in creep behavior of thermally bonded and needle-punched nonwovens was analyzed using creep and tensile tests. It was shown that increased loading resulted in the increase time dependent creep strain with the creep behavior of needle-punched nonwovens having a logarithmic dependence on time. It was reported that discontinuous and heterogeneous micro-structured low density thermally bonded nonwovens displayed an unstable tensile behavior. To investigate this statement, a study was carried out to assess the effects of specimen size, shape factor, and cyclic tensile loading conditions on the deformation behavior of low density thermally bonded nonwovens using experimental methods, FEA and microscopic image analysis. A new numerical method based on parametric FEA was developed and implemented to investigate the creep behavior of low density thermally bonded nonwoven structure (see Figure 3). By employing some qualified benchmarks for different types of nonwoven structures with distinct geometrical and material parameters, it was indicated that employing elasto-plastic material behavior made the slope of the deformation curve closer to the results obtained from experimental studies. Yet, implementation of bond points and creep behavior in the finite element simulation slightly affected the tensile and creep results of the specimens (see Figure 4). Complex deformation analysis of a polypropylene based fabric was performed using tensile, creep, and relaxation tests and a novel finite element analysis methodology. It was shown that the proposed numerical model successfully predicted the stresses at each finite element and, thus, this could unveil the higher stress areas with ease. Then, Kelvin, Burger, two-term generalized Kelvin and Zurek mechanical models were utilized to investigate the creep response of nonwoven fabrics. The findings of that study were compared with the experimental data and it was concluded that Burger mechanical model had high accuracy in defining the creep behavior of nonwovens. The numerical modeling of a thermally bonded nonwoven using a macro-scale based classical laminate composite theory was carried out to analyze the experimental stress–strain results. It was established that the matched results could be used to further investigate the stress relaxation, creep, and bending behaviors of the nonwoven fabrics.

Bending behavior

A proper assessment of bending behavior in nonwoven materials is quite important because in real life applications these fabrics usually encounter bending loads. For instance, nonwoven filter materials need to withstand excessive bending loads exerted by the fluid pressure. Assuming that the fibers have a linear tensile and shear stress–strain behavior, the effects of tensile, and torsional stiffness of fibers and their diameter on bending rigidity of nonwoven fabrics were studied using an analytical approach and experimental methods. It was found that a unit cell model without relative fiber motion was more efficient than the one with complete freedom of relative fiber motion in capturing the bending rigidity accurately. Later, a self-consistent analytical model was developed to investigate the bending behavior of locally heterogeneous nonwoven fabrics (see Figure 5 for the continuum representation of free fibers as a matrix). Coupled experimental and numerical studies revealed that self-bonded nonwoven fabrics could withstand higher bending stresses with superior extensibility in both tension and
Figure 4. Force–displacement plots for different types of material formulations: (a) elastic fiber and bond points, (b) elasto-plastic fibers and elastic bond points, (c) elasto-plastic fibers and bond points, and (d) elasto-plastic fibers and bond points with creep.

Figure 5. Continuum representation of nonwoven with free fibers as matrix.

Apparently, although the analysis of the bending behavior of nonwovens is important for their applications, there seems to be only few relevant studies. The effects of fabric drape characteristics and anisotropy constants on bending rigidity of thermally bonded nonwovens were investigated. Then, bending behavior of stitched nonwoven fabrics was studied by considering various values for stitch density, stitch angle, and stitch line spacing and it was found that rupture of the stitched fabrics was mainly influenced by the last two parameters.

Dynamic behavior

Understanding of time dependent behavior of nonwovens is important for prediction of their long term behavior as especially in civil engineering applications, these materials should have a considerable life in service. According to the literature, there are not many studies related to their dynamic behavior. Some are only focused on finding the storage and loss moduli of these materials by utilizing several dynamic tests. In general, researchers use a Dynamic Mechanic Analyzer (DMA) device (Figure 6) to assess these storage and loss moduli of the nonwoven fabrics by applying very...
low strains (less than 0.5%). The difference in the storage modulus, which characterizes the elastic behavior, and the loss modulus, describing the viscous one, can be used to assess the damping capacity of the nonwoven fabric.44

A dynamic internal bond strength method was used to measure the internal bonding energy between the laminates.46 This method can accurately measure the bonding energy of the nonwovens produced with the hydro entanglement method. In another study,47 aramid nonwoven interlayers were employed along with fiber reinforced composite laminates with (fiber ratio of 0.5) to prepare a co-cured composite to investigate the dynamic behavior and damping capacity of nonwoven fabrics. By using DMA on a prepared sample, it was shown that interleaved aramid nonwoven fabric layers greatly increased the damping capacity and fracture toughness without compromising its shear strength. This study was extended in48 to investigate the effect of polyamide nonwoven fabrics (PNF) on the storage and loss moduli and concluded that utilizing PNF could improve the loss factor without a significant alteration on the storage modulus. Later, the dynamic behavior of melt blown shape-memory nonwovens was investigated using experimental methods that depend on DMA.49 In that study, small rectangular samples were tested by applying 0.1% strain at frequency of 1.0 Hz and it was concluded that the increasing collector speed greatly affected the elastic modulus and recovery stress of the nonwoven fabrics. Different types of degradation tests were utilized to assess the mechanical damage by using different types of nonwoven fabric samples that are pressed between two aluminium oxide layers in a pressure range from 5 to 500 kPa with 1 Hz frequency up to 200 times.50 These tests significantly decreased the tensile strength, tearing strength, and static puncture resistance of nonwoven fabrics.

**Damage behavior**

One of the most difficult types of research is on the damage characteristics of nonwoven materials. As the fibers and bonds between them are randomly distributed, it is generally difficult to estimate their behavior, with different batches reveal different results. The damage related studies are also relatively recent as advanced imaging and simulation techniques were needed. These types of studies are the most active research topic of nonwovens due to the needs of industry. Most of them start with the investigation of a single fiber rupture and then addition of other manufacturing related concepts such as, bond point failure, cluster breaks effect of notches, etc.

Initially by,51 a computer simulation and numerical analysis based on fiber rupture criterion was developed to determine the failure strength and damage progression in nonwoven fabrics. With the help of finite element algorithms, the loading required to break the fibers obtained together with the stress and strain distributions in different regions of nonwoven fabrics was successfully presented. The damage micro-mechanism for a glass-fiber based nonwoven felt was analyzed using experimental and numerical simulations by utilizing tensile tests on notched and unnotched rectangular samples.52 It was found that the fracture between the bundles led to a localized damage in the interbundle bonds; however, complete fracture did not occur immediately. Complex damage initiation in low density thermally bonded polymer nonwoven fabrics was studied using micro-scale discontinuous finite element analysis and Hough transformation.53 It was concluded that this analysis was very accurate in determining the damage initiation. Later, the damage characteristics for a polypropylene fiber nonwoven was investigated using an experimental method based on single-fiber failure and the obtained results were validated using numerical simulations,54 that employed a combination of shell and truss elements presented in Figure 7. Using single bond breaking processes and local damage events at macroscopic scale, a new non-linear damage model was presented to reproduce the experimentally observed behaviors such as elasticity and non-linear hardening.55 This new nonlinear model allowed predictions of the damage zones ahead of the crack tips (see Figure 8 for damage contours). Damage evolution in thermally bonded nonwovens was studied recently in56 based on a combination of experimental studies and finite element simulations of specimens with notches of different shapes. Some results are presented in Figure 9.
Conclusion

The aim of this review was to assist a reader to understand the background of research into mechanics of nonwoven fabrics focusing on previous and recent works. The observations according to literature can be summarized as follows:

• The tensile behavior of different types of nonwovens was understood reasonably well with many studies performing tests and simulations for various types of nonwovens.

• Studies related to bending behavior of nonwovens are limited. Especially, the bending performance according to various bonding types can reveal interesting results.

• Dynamic behavior studies came up to a level. This area can be interesting for the researchers for the development of these materials for shielding applications.

• Damage related studies are very challenging for these materials due to their stochastic micro structure.

The future of nonwoven research seems to be shaped more towards the needs of industrial applications. In the short term, the bending behavior and its relation to manufacturing parameters should be explored further. Fiber–fiber mechanical interaction under different loading schemes is expected to be researched as significant friction can be observed in micro-scale videos. Environmental effects such as temperature and humidity should be assessed more deeply considering the application area of nonwovens. Fatigue is an interesting research area for these materials as it is affected by the creep behavior as well. Together with fatigue, the environmental effects after a period of service is also important and can affect their mechanical performance. Comparison of the behavior of used and brand new nonwovens can reveal invaluable information for the designers. For instance, for filter applications, in long term particles can accumulate on the surface – causing them to rupture earlier than expected. Developments in the simulation types are also expected and various tools – specific for nonwovens – is expected to be developed regarding transient dynamic analysis, micromechanics, orientation distribution to explain their damage and time dependent behavior.

Figure 7. Magnified view of bond point with truss and shell elements.54

Figure 8. Damage contours of notched SF32 nonwoven fabric: (a) $\epsilon = 0.06$ %70 of peak load; (b) $\epsilon = 0.16$ peak load; (c) $\epsilon = 0.20$ %70 of peak load; (d) $\epsilon = 0.25$ %10 of peak load.55
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Figure 9. Comparison of experimental and simulated damage patterns for specimen with slit notch for 0%, 60%, 80%, and 100% extension.56
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