NONWOVENS MODELLING: A REVIEW OF FINITE-ELEMENT STRATEGIES

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Abstract

This paper reviews the main strategies used to simulate the mechanical behaviour of nonwoven materials that is defined by a structure of their fibrous networks and a mechanical behaviour of constituent fibres or filaments. The main parameters influencing the network structure of nonwoven materials are discussed in the first part. The second part deals with two main strategies employed in the analysis of mechanical behaviour of nonwoven materials using finite-element models based on continuous and discontinuous techniques. Both strategies have further sub-types, which are critically reviewed, and future trends in this area of research are discussed.

Key Words

Nonwovens, mechanical properties, thermal bonding, finite-element modelling

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1. Introduction

Nonwovens are the oldest type of textile known to the man, existed before the weaving and knitting processes. It was used in times of antiquity in both Asia and Europe (Burkette, 1979; Laufer, 1930).Nonwovens are engineered materials manufactured from a set of disordered fibres, or filaments, bonded together with a mechanical, thermal or chemical bonding technique. The type of bonding process used together with the fibre properties determines, to a large extent, properties of the resulting material. In chemical bonding, liquid adhesives are used resulting in a densely bonded structure (Picu, 2011). If mechanical bonding such as hydro-entangling is employed, consolidation of the web is achieved by inter-fibre friction as a result of physical entanglement of fibres (Edana, 2013). The process of thermal bonding exploits thermoplastic properties of some synthetic fibres to form bonds under controlled heating. Thermal calendered bonding is produced by bringing such polymeric fibres in contact with a heated punch, results in a patterned bonded network while through-air thermal bonding makes bulkier products by overall bonding of a web containing fibres with a low melting point.

Nonwovens are not only the low-cost replacement for more expensive woven textiles but also can be engineered for particular characteristics (e.g. fire resistant, abrasion resistant, absorbent, liquid repellent etc.) making them suitable for many applications such as filters, protective clothing, absorbent hygiene products (baby diaper, feminine hygiene products), ballistic protection etc. (Russell, 2007). Still, new materials based on this technique continue to emerge thanks to their analogy with biological materials such as collagen and tissue-engineering scaffolds, in which structures made from fibres are ubiquitous (Ridruejo *et al.*, 2010; Picu, 2011). This ability has made the nonwoven industry more competitive in terms of tighter product specification. A significant part of nonwovens' consumption is related to structural and mechanical purposes (Edana, 2013), which require appropriate knowledge of mechanical behaviour and structure-properties relationship of these materials. Additionally, as engineered materials, nonwovens have a great potential to widen the spectrum of applications, which demand an insight into their mechanical behaviour. However, it is a challenge to design and manufacture a nonwoven according to particular requirements involving numerous time-consuming and expensive trial-and-error stages. In order to reduce the resource-extensive optimization stages during design and development of nonwoven products and improvement of existing products, a numerical modelling technique can be utilised. Besides, experimental characterisation of a nonwoven material is not always viable and/or sufficient for a comprehensive understanding of complex phenomena involved in their deformation and damage behaviours. The challenges related to experimentation may be linked to the lack of specialised experimental facilities or significant efforts required for implementation a necessary test program, especially for nonwovens, which mechanical properties are defined by their microstructure and constituent fibres' properties. Thus, numerical simulation is an economical alternative for predicting the behaviour of this type of materials.

A mechanical response of nonwovens is generally very complex, involving nonlinearity and anisotropy, governed by elastic-plastic mechanisms (e.g. fibre rotation and stretching) (Farukh *et al.*, 2013a; Jearanaisilawong, 2008), viscoelastic mechanisms (e.g. fibre relaxation or creep) and additional irreversible mechanisms (e.g. fibre slip, fibre failure and bond breakage). A finite-element method has been used to study various aspects of mechanical behaviour of nonwoven materials such as axial stress-strain behaviour including elastic stiffness under monotonic loading (Hou *et al.*, 2009: Silberstein *et al.* 2012), mechanical performance under complex loading histories including out-of-plane loading (Farukh *et al.* 2013; Demirci *et al.*2013), a notch-sensitive behaviour (Ridruejo *et al.* 2010), mechanisms involved in deformation and damage (Farukh *et al.* 2014) as well as effects of manufacturing parameters on mechanical performance of nonwovens materials (Sabuncuoglu *et al.*, 2012). However, most of the studies were focussed on a particular aspect of mechanical behaviour of nonwovens while fully or partially neglecting others. To develop a finite-element model incorporating all these mechanisms and predicting the macroscopic response of the fabric while keeping it computationally efficient is very challenging. Therefore, different strategies were adopted in the literature to simulate nonwoven materials and predict their behaviour (Jearanaisilawong, 2008). These strategies differ from each other mainly on the basis of the method employed to idealise a structure of the modelled nonwoven material. Understanding of advancements in this field and future trends will help scientists and engineers dealing with numerical modelling of nonwovens as well as designers and manufacturers to fully employ their potential in future applications.

2. Network structure

The notion of network structure refers to a set of parameters determining the deformation behaviour of nonwovens. Since the variation in these parameters affects the mechanical performance of nonwoven materials and a difference between main modelling strategies is based on them, therefore, they are discussed here. Besides, they will help explaining the advantages and drawbacks of different strategies for modelling nonwovens in a better way.

Parameters characterising the network structure include orientation distribution of fibres, cross-links between them, nature of bonding, bonding density and length, diameter and density of constituent fibres. The details on how these parameters affect the behaviour of the fabric can be found in (Farukh, 2013). The classification of nonwovens based on these parameters is shown in Fig. 1. Most of the finite-element (FE) models in literature are developed to predict either the behaviour of a specific type of nonwovens (Farukh, 2013). Besides, researchers were focussed on different length scales such as micro (Hou *et al.*, 2009), meso (Liu *et al.*, 2013) or macro scales (Demirci *et al.*, 2011) and corresponding phenomena. As a result, different modelling strategies were developed to simulate nonwoven materials in order to meet the requirements at different length scales. These modelling strategies with their advantages and shortcomings are discussed in the next section.

3. Modelling strategies

Simulation of mechanical behaviour of nonwoven fabrics using finite-element models based on their method of idealization of the network’s geometry can be classified into two major categories: continuous and discrete models. Each of these categories, in their turn, can be sub-divided into two modelling techniques; the flow chart showing these techniques is given in Fig. 2. In case of nonwoven materials, a micro-level corresponds to the individual-fibre behaviour and a macro level refers to the overall response of the fibrous network, whereas a meso-level means the localised response of a small part that is big enough to characterise the material.

3.1 Continuous modelling technique

In the continuous modelling approach, the fibrous network of nonwovens is idealized as continuous medium. The mechanical behaviour of nonwoven is simulated by applying appropriate material properties to the corresponding elements. This modelling approach can be further divided into two techniques based on the method of incorporation of the effect of non-uniform fibre orientation: homogenous components structure and composite-continuum structure.

The former approach treats the nonwovens at the macroscopic level as a continuum. Earlier examples of this modelling technique include the models by Backer and Petterson (1960). This modelling strategy does not retain any information related to fabric's microstructure such as bond pattern in the area-bonded fabric and random distribution of fibres. In order to incorporate information linked to the structure of the fabric, Demirci *et al.* (2011, 2012) idealized the geometry of nonwoven fabrics with a continuum model (Fig. 3) based on orthotropic symmetric planes. The size, shape and pattern of bonding area were incorporated into the model explicitly. However, randomness in orientation of fibres of the fabric (also reflected in the orientation distribution function) was introduced as orthotropic parameters calculated by using the specially developed software. This model was rather useful for predicting the stress—strain behaviour of high-density nonwovens accurately but damage initiation and propagation was not accounted by it. Since the model was based on the continuum approach, it was incapable to account for fibre-level mechanisms involved in deformation and damage of nonwovens. Based on the same modelling technique Ridruejo *et al.* (2012) introduced a continuum model to predict a meso-level response of the fabric but fibres were not explicitly introduced into their model; rather, a constitutive relation concerning with fibre orientation distribution was suggested. Since this continuum model was developed to predict the fabric's behaviour at meso-level, it was unable to mimic the actual microstructure and mechanisms of fabric's deformation. Besides, damage mechanisms (fibre stretching, breaking and pull-out etc.) were implemented in the order they were observed experimentally, rather than inferring the causes for these. Thus, the major limitation of the models based on the continuum modelling technique is the absence of information about microstructure of the fabric and its deformation and damage mechanisms under loading conditions that cannot be studied with this modelling strategy. However, these models are computationally very efficient and can be used to predict the overall macroscopic behaviour and performance of the fabric. Since this strategy is based on continuum modelling technique, it is more suitable for high-density nonwovens (> 50 g/m^2) rather than low-density ones, which structure is characterised by a significant amount of voids and gaps.

The second approach, a composite continuum structure, based on a composite laminate model, incorporating the effect of non-uniform orientation distribution of fibres, was used by Adanur and Liao (1997) and Bais *et al.* (1998). The nonwoven, assumed as a continuum, was made of several mono-directional fibre layers; within each layer fibres were oriented in statistically determined direction. All the fibres in one layer were oriented in the same direction as shown in Fig. 4. The layers were stacked on top of each other, with a relative angle between fibres in them in a way that the overall arrangement gave the average fabric anisotropy (Fig. 4). These layers were stacked and bonded along the entire contacting interface. The fibres were bound together at nodal point of a finite-element mesh.

The models deal with deformation of fabric as the individual fibres incrementally break. These models were stated to produce satisfactory results, in agreement with experimental studies, including aspects of fibre anisotropy arising from non-uniform orientation distribution of fibres, particularly in a small-strain regime. However, representation of the real deformation mechanisms such as non-uniform stretching and reorientation of fibres were not reflected since the fibres were fixed within the layer, which could not slide with regard to each other. Furthermore, the models based on this strategy do not contain realistic fabric's microstructure and, thus, are unable to provide information about structural evolution based on fabric's extension. Additionally, realistic distributions of stresses and strains in fibres cannot be obtained with this modelling strategy; these are vital for designers and manufacturers of nonwovens to produce more reliable and durable materials. However, the models are computationally efficient and suitable for macro-scale modelling of nonwovens.

3.2 Discrete modelling technique

In discrete modelling of nonwovens, fibres are modelled explicitly in a specific pattern to incorporate irregularities in the microstructure of fabrics, such as voids and gaps in the fibrous network, into the model. Due to the technique involved in developing of this type of models, they can be called *complex fibre-network's structure models*. The discrete modelling technique can also be divided into two sub-categories: (i) a technique based on a representative volume element (RVE) and (ii) a direct fibre introduction method.

In an effort to incorporate the realistic effect of non-uniform microstructure of nonwovens into the model, a discrete modelling approach based on homogenization of RVE was used in the literature. Petterson (1958) introduced the model to predict the macroscopic response of the fabric by homogenizing the behaviour of a unit-cell accounting for random distribution of fibres' orientation. This model was later modified by Hearle *et al.* (1964) and again by Kothari and Patel (2001), to include the effect of fibres and a creep response of individual fibres, respectively. Still, in that model, some inelastic deformation mechanisms, such as irrecoverable textural evolution, were missing. More recently, Silberstein *et al.* (2012) introduced a model based on a similar RVE-based technique to predict a macroscopic behaviour of the fabric. The model consists of a multilayer triangular network and uses a homogenization technique to predict a response to monotonic and cyclic loading. Such models based on the homogenization technique do not predict localization of damage and changes in material's microstructure caused by this damage. However, the model can be used to study the global axial stress-strain behaviour and transverse strain in nonwovens. Additionally, this model overcame the shortcomings of previous models based on the same RVE-based modelling strategy and can predict the mechanical response of nonwovens under cyclic loading. Since the nonwoven's microstructure is idealised with the triangular network with elastic-plastic fibres, the effect of stretching and bending of them as well as their interaction under small-load regimes can also be studied. Alongside this, another potential benefit of this approach is a quick and easy generation of the nonwoven network model as it is merely the repetition of RVE.

Another discrete modelling approach used to incorporate the randomness of nonwoven material into the model is by direct introduction of fibres to simulate a realistic deformation and damage behaviour of nonwovens. In this context, Mueller and Kochmann (2004) and Limem and Warner

(2005) proposed a FE model to simulate the behaviour of thermally bonded nonwovens (Fig. 5). In these models, unit cells based on direct introduction of fibres were developed and used repetitively to predict the macroscopic response of the nonwoven fabric under loading.

With the RVE-based models, the effect of geometry of bond points on the behaviour of nonwovens was also investigated. However, it was almost impossible to incorporate the randomness in the microstructure of the nonwoven into the model as it was composed of a periodic network of symmetric unit cells, and there was a limited number of nodes on the bond point. Moreover, it failed to mimic the microstructure of the nonwoven fabrics. Thus, the actual mechanisms involved in deformation and damage of nonwovens cannot be studied using these models. The omission of realistic microstructure leads to inaccurate repetitive distributions of homogenised stresses and strains in the nonwoven network under macroscopically uniform loading conditions.

Models of nonwovens based on the complex fibre-network's modelling technique were developed incorporating realistic orientation distributions of fibres and other parameters of the network. A recent development in this type of discontinuous modelling of nonwovens was made by Hou *et al.,* 2009. They proposed a discontinuous model with a realistic distribution of fibres and bond-point structure (Fig. 6). This was a suitable technique to imitate the geometry of the fabric network including voids and gaps in their microstructure. Since it was difficult to model all the fibres in the structure, one of the weaknesses of this model was convergence issues due to a limited number of fibres modelled between the bond points. Besides, it was rather difficult to incorporate different realizations of orientation distribution of fibres, and various sizes, shapes and patterns of bond points. Therefore, it was almost impossible to apply this model for another type of nonwoven especially with a higher planar density.

To overcome these shortcomings, a parametric finite-element strategy based on direct introduction of fibres into the model was suggested in Sabuncuoglu *et al*. (2012, 2013a) and further developed by Farukh *et al.* (2012, 2013a, 2013b, 2014). Such a parametric model has the advantage to implement the changes in parameters such as the number and orientation distribution of fibres, size, shape and pattern of bond points easily. Fibres between the bond points were modelled according to their orientation distribution in the real fabric. The model was capable to predict the effect of various parameters on deformation behaviour of nonwovens under monotonic loading. It provides an insight into localization of damage and a change in network topology as a function of damage evolution along with the mechanisms involved in it. This modelling technique is computationally not as efficient as a continuum one; however, it can account explicitly for all the main mechanisms involved in deformation and fracture of nonwovens. Moreover, a model based on this technique naturally introduces voids and gaps into consideration that are a distinctive feature of fibrous networks especially in case of low-density nonwovens. Due to the explicit inclusion of microstructure, it is suitable for micro or meso scale modelling of nonwovens, where the study of mechanisms involved in deformation and damage of nonwoven materials is important. Since this technique is computationally very expensive, it is suitable only for low-density nonwovens or for analysis of a global response of comparatively small areas of a fabric.

Thus, each modelling strategy has its own benefits and shortcomings and is suitable for particular scale, type of nonwovens and other requirements as summarised in Table 1.

4. Conclusions

Detailed knowledge of mechanical behaviour of nonwoven materials is essential in design of products containing them. Numerical simulations help in understanding complex damage and deformation phenomena of fibres and are an alternative to the trial-and-error approach in design and development. The critical study conducted for various modelling techniques employed in simulations of nonwoven material demonstrated that the continuous modelling technique is best suited for macro-scale modelling, whereas the RVE-based schemes and the complex fibre network (a sub-category of discrete modelling) are suitable for meso- and micro-scale modelling, respectively. Among all, the last technique has an added advantage of quantifying fabric microstructure, deformation and damage mechanisms as well as realistic distribution of stresses and strains at the expense of higher computational cost which make it suitable just for low-density nonwovens or to model small areas of fabrics. Still, the future models should additionally account for a fibre-curl distribution as well as effects of creep/stress relaxation. Another development in FE modelling of nonwovens, which is most likely to be carried out in the future, is account for the interaction between fibres in out-of-plane loading. This will allow for analysis of compressional behaviour of nonwovens, typical example being air and water filters, and for a study of mechanical behaviour of nonwovens under impact loading regimes, with a typical example of body armour.

This review should help researchers to choose a suitable strategy - or a combination of strategies - to obtain desired results while keeping it computationally efficient. Since the paper is focused on modelling strategies for nonwovens rather than on the detailed description of models, a limited number of examples relevant to each strategy were included.

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Modelling technique		Computational efficiency	Useability	Realistic microstructure	Deformation and damage mechanisms	Fibre stress/strain distirbution
Continuous modelling	Homogenous components sctructure	Less expensive	Macro-scale modelling	No	No	Not possible
	Composite continuum structure	Less expensive	Macro-scale modelling	No	No	Not possible
Discerete modelling	Represetative Volume Element based modelling	Fairly expensive	Meso and macro-scale modelling	No	No	Homogenous stress/strain distribution can be obtained
	Complex fibre network	Very expensive	Micro-scale modelling	Yes	Yes	Realistic stress/strain distribution can be obtained

Table 1. Summary of modeling strategies

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Word count

3905

Disclosure Statement

The authors have no financial interest or benefit arising from the direct applications of their research.

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Figure 1

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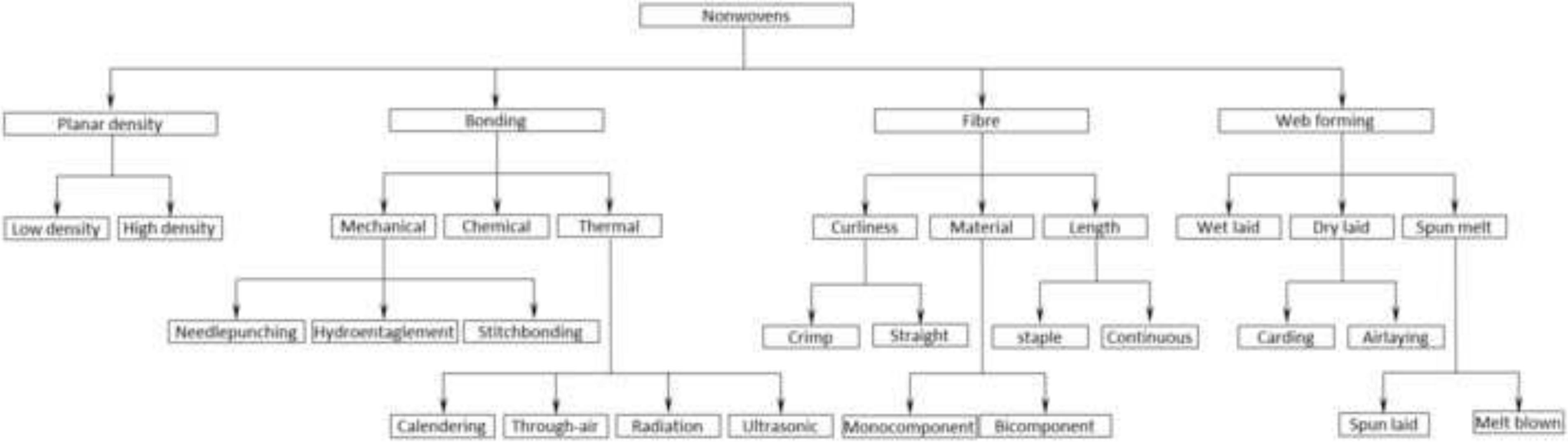


Figure 2

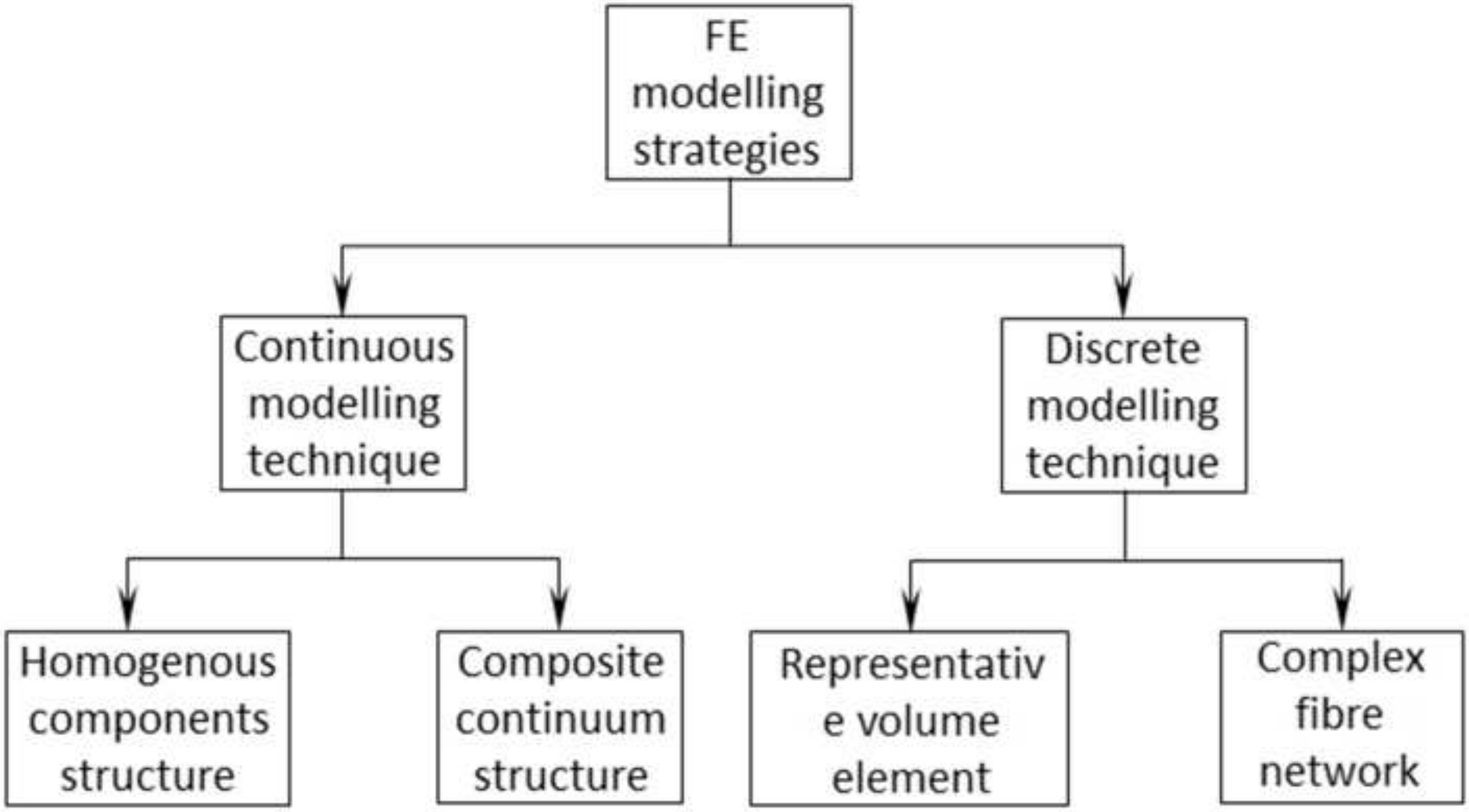
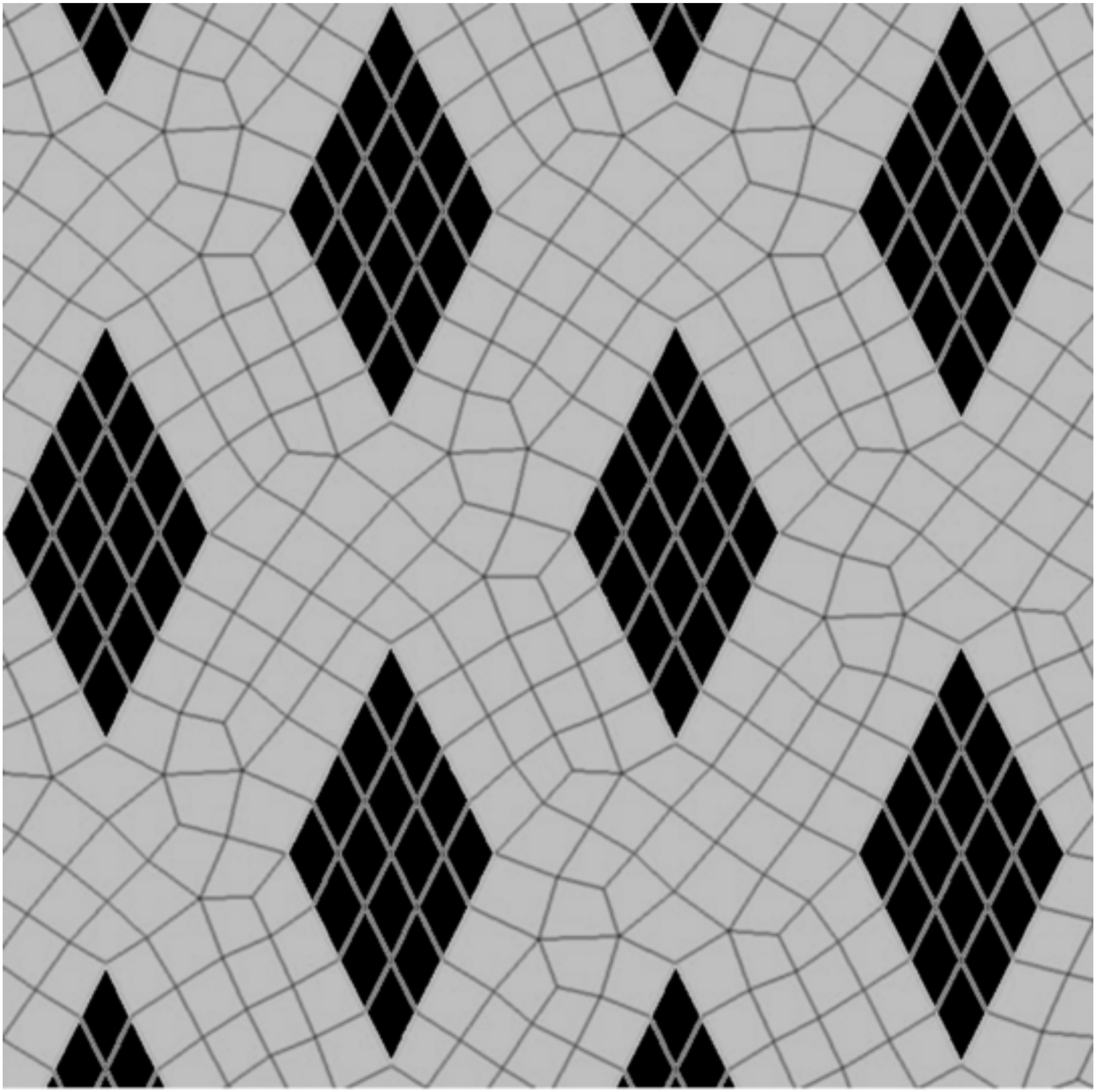

FE modelling strategies
Continuous modelling technique
Discrete modelling technique
Homogenous components structure
Composite continuum structure
Representativ e volume element
Complex fibre network

Figure 3



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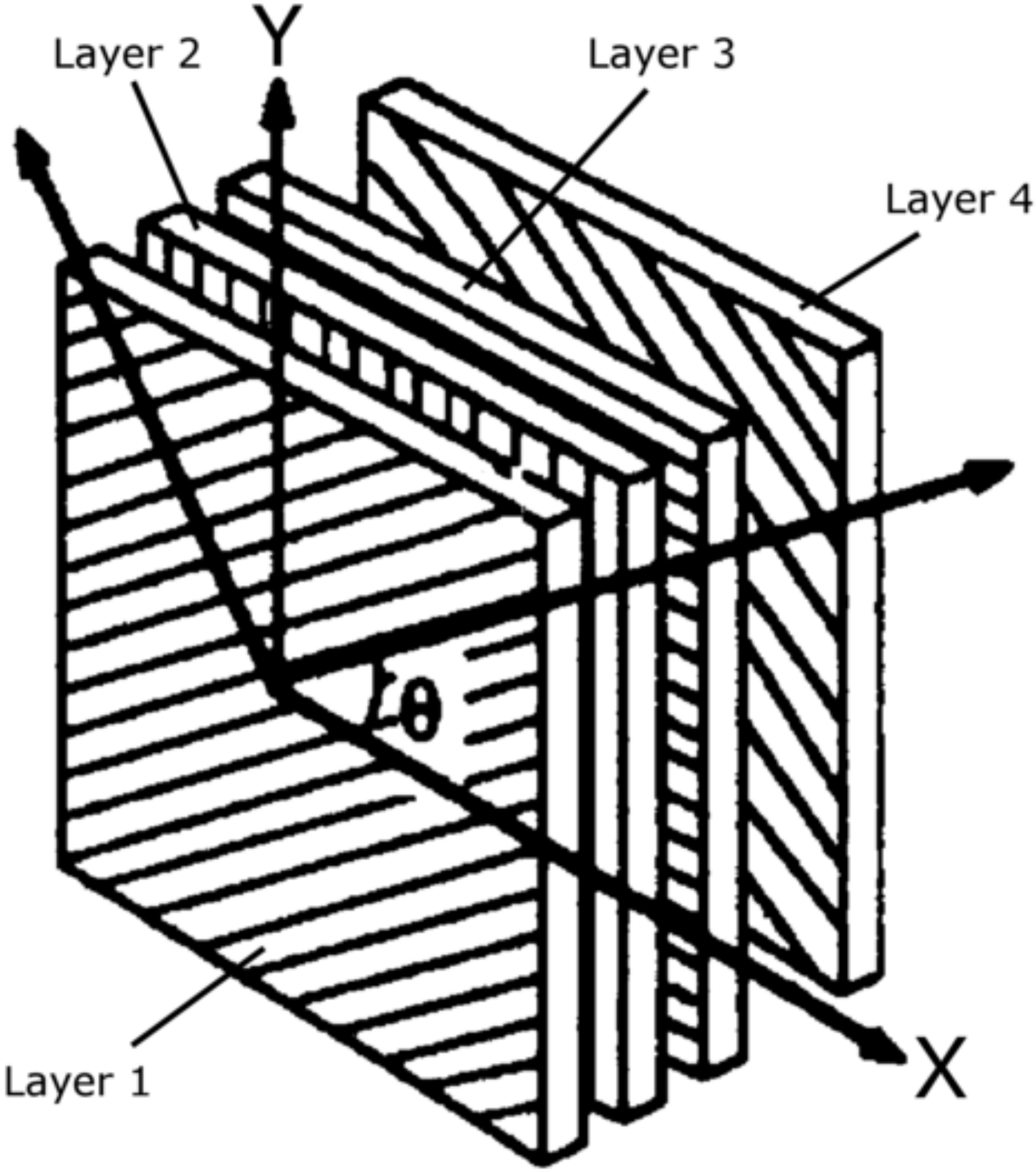

Figure 5

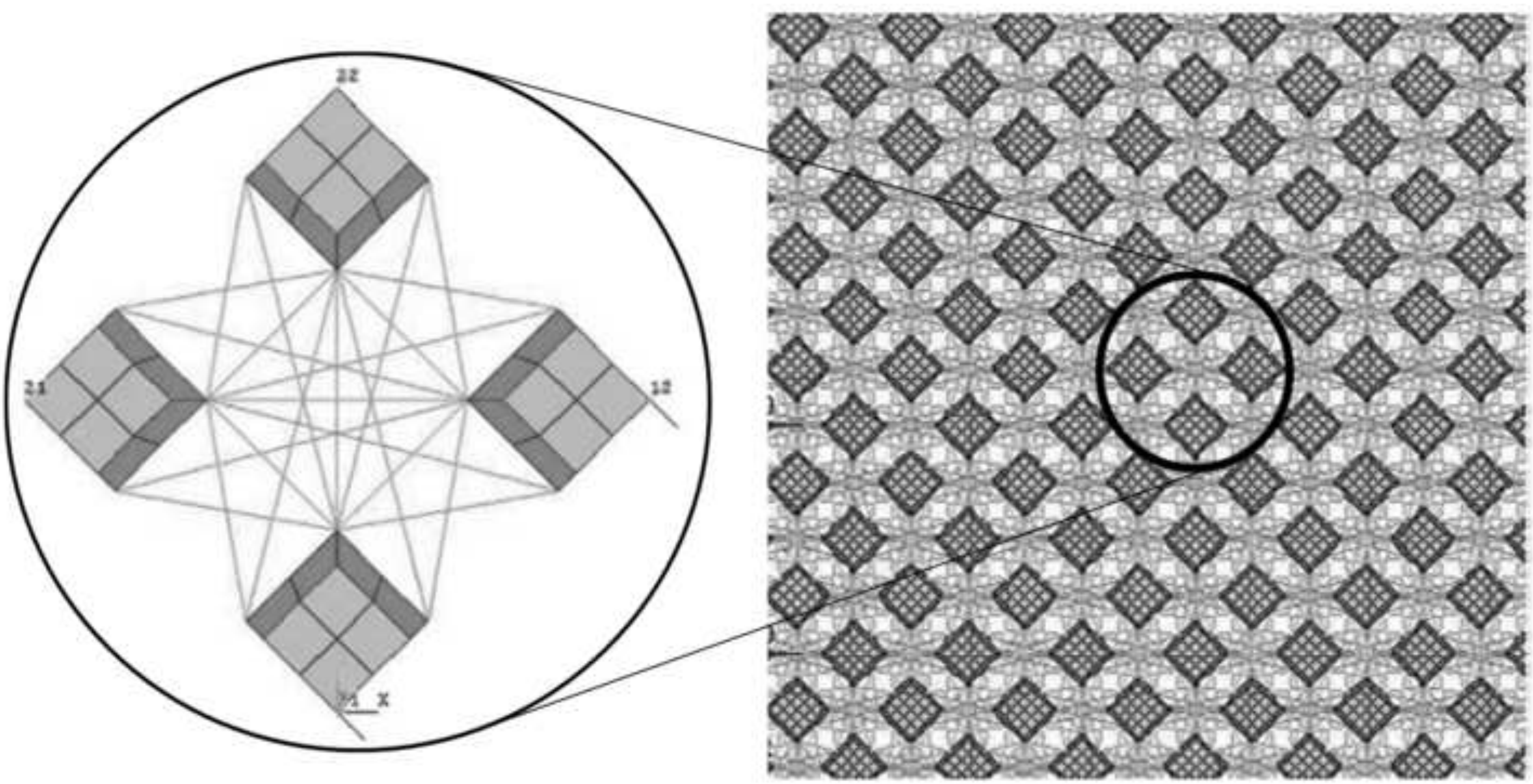

Figure 6

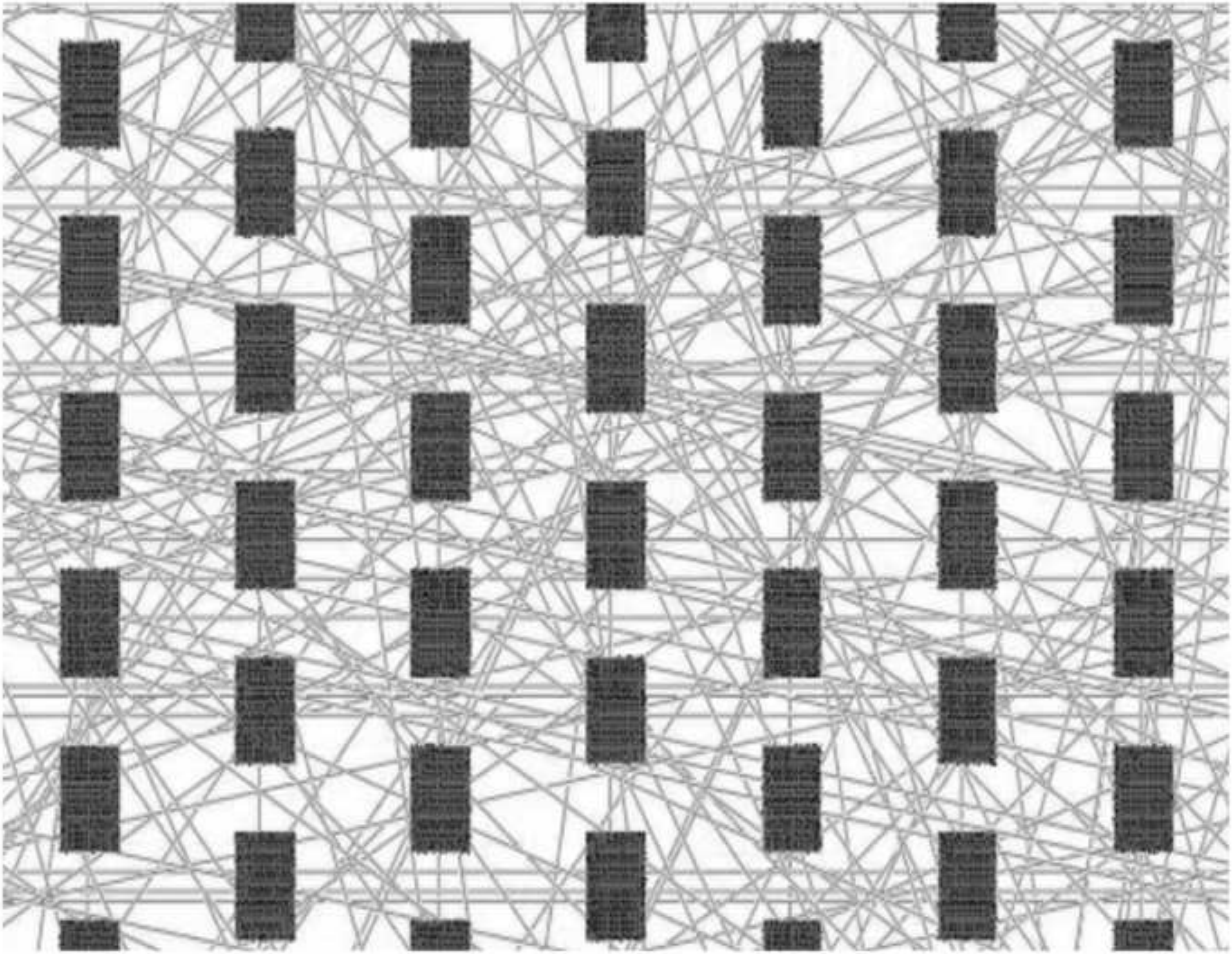

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Table 1. Summary of modeling strategies