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Numerical Modelling of the Compressional Behaviour of Warp-knitted Spacer Fabrics

Abstract
Warp-knitted spacer fabrics are successfully introduced in building constructions as a thin sheet component reinforcement for wall panels, exterior siding, roofing tiles, flooring tiles, pressure pipes etc. Their structural advantages support an armature system of highly oriented yarns and easy cement embodiment for the production of a composite. The compression resistance of spacer fabric is a major advantage with respect to the performance and composite manufacturing process. The optimum compression performance of spacer fabrics varies according to the requirements of the application in question. This investigation focused on the prediction of the compression performance by two-scale (micro and macro) mechanical analysis using the Finite Element Method (FEM). Micromechanical analysis of the unit cell of the spacer layer was conducted for the calculation of its compression resistance. The apparent mechanical properties of the outer layers were also evaluated by micromechanical modelling. The respective properties of the outer and spacer layers are introduced in the macromechanical model of the sample for analysis of the complex deformation during simulation of the compression test, thus realising the second stage of modelling. The computational method proposed is evaluated by comparison of the load – displacement curves resulting from the simulation and experimental data of compression. Moreover, the effect of the structural and physical parameters of the sample on the compression resistance was investigated.

Key words: *spacer fabric, compression resistance, Finite Element Method.*

speed, which is supported by the warp knitting in two-needle-bar Raschel machines.

Spacer fabrics present special characteristics compared to conventional textiles due to their structure. The compression resistance is beneficial for the structural stability of spacer fabrics, suitable for permanent or instant loading and recovery. An even distribution of pressure or the respective even damping effect can be achieved by the selection of appropriate yarns and patterns. The control of air permeability, heat and moisture transport between the environment and the outer layers offers a great advantage for special applications. Semi-permeability is also possible by selecting outer layers of different attributes. The microclimatic quality in conjunction with the compression ability of the spacer fabrics offers potentially adequate physiological comfort. Moreover, the low weight of spacer fabricsis essential for their use as reinforcement elements for composites when light constructions are required. Furthermore, the ability of spacer fabrics to embody functional components allows it to be used in the manufacture of multifunctional products.

The wide range of materials and patterns used for the production of spacer fabrics and the subsequent range of resultant properties justify the extended application areas of spacer fabrics. Actually, the applications of spacer fabrics range from the garment sector to reinforcement applications, including the following areas: automotive, medicine, geotextiles and environmental protection, civil engineering, sports and leisure, safety and protection [1].

Warp-knitted spacer fabrics could be successfully used as reinforcement components for concrete applications due to their beneficial characteristics [2]. The capability of manufacturing warp-knitted spacer fabrics using technical fibers (glass, carbon, aramid etc) is essential, as the well known advantages of conventional "single layer" fabrics (high tensile resistance in oriented directions, durability against corrosion, low weight,

◼ Introduction

Spacer fabrics are three-dimensional textile structures consisting of two outer textile surfaces connected by an inner layer (spacer layer) appropriate for the formation of space between the surfaces (*Figure 1*). Several techniques can be applied for the production of spacer fabrics using woven, weft and warp knitting technology. Warp knitting is the most commonly used technology for the production of spacer fabrics, providing several advantages: among others, the wide range of yarn types and fabric thicknesses. Another advantage is the high production
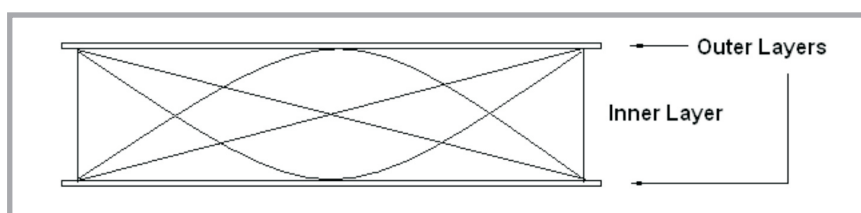

Figure 1. Structure of a spacer fabric.

etc [3, 4]) could be combined with the special characteristics of the product in question. In fact, the relatively high compression resistance offered by spacer fabrics ensures stability of the product in the third direction (perpendicular to its surface), preventing deformation of the outer layers. Spacer yarns are presented as highly oriented in the total structure, forming "truss" elements and also providing stiffness in the third direction. It should be noted here that the flexibility of conventional "single layer" fabrics, comprises their main properties, making them particularly suitable for the "external" repair of damaged concrete members [5]. Thanks to their stiffness in the third direction, warp knitted spacer fabrics provide stability during the construction procedure and concreting under in-situ, but especially under precast quality controlled conditions. As a consequence, they could be easily used as "inner" reinforcement for concrete members, in the position where steel reinforcing bars are conventionally used. Moreover, thanks to the stability of spacer fabric, the embodiment of the concrete is easily achieved (for example, by injection molding), allowing the development of cohesion forces between the concrete and spacer fabric, permitting the transfer of tensile forces along the crack. In addition, the online production of warp-knitted spacer fabrics in one production step can be described as a profitable manufacturing procedure.

Due to their aforementioned beneficial characteristics, warp-knitted spacer fabrics could consist of an armature solution that is profitable and can compete with conventional reinforcing systems: thin sheet component reinforcement capable of retaining its position and carrying the weight of net concrete during concreting as well as the high amount of tensile forces under service conditions by appropriate arrangement of the technical fibers of the outer layers (usually in two perpendicular directions). This could be extremely useful, especially for precast plane or shell concrete members i.e. load or non-load bearing precast concrete wall panels for precast industrial buildings and housing [6], industrial flooring tiles, precast concrete segments for underground structures, etc.

The compression resistance of spacer fabrics is a critical factor for the performance and composite manufacturing process, as well as for the embodiment of t spacer fabrics in concrete structures, as

an innovative armature system. The optimum compression performance of spacer fabrics varies according to the specific application requirements. Modifications in the design parameters of spacer fabric affect its structural characteristics and, consequently, the compression resistance of the sample. The purpose of the current investigation is the parametric analysis of the structure of spacer fabric in which the effect of certain parameters in compression deformation is defined.

■ Materials and methods

Samples used

The warp knitted spacer fabrics under investigation were produced on a double needle bar Raschel machine type HDR 6-7 DPLM, Karl Mayer Textilmaschinenfabrik GmbH, Obertshausen, specially modified for concrete applications at the ITA, RWTH Aachen University, Germany [7]. The modifications comprise additional insertion yarn systems in the warp and weft directions. Thus a grid net-like structure is available for the outer surfaces, increasing the facility of cement penetration within the yarns.

The principle of production consists of the simultaneous production of the outer surfaces, each one independently made on each side of the machine. The spacer layer is also formed during the production of the outer surfaces by another set of needles. The length of the connecting yarns can vary between 3 mm and 160 mm, resulting in a flexible range of spacer fabric thickness [7].

The study proposed is focused on a group of warp-knitted spacer fabrics prepared by ITA, RWTH Aachen University. Properties of the spacer fabric components are given in *Table 1*. The 0° and 90° yarns correspond to the warp and weft inserted yarns of the outer layers. Spacer yarns connect the two outer surfaces forming the spacer layer. The warp knitting yarns create the binding of the structure in the knitting process. A group of samples was produced keeping constant the materials and patterns used for the warp knitting yarn, the 0° and 90° yarns, spacer yarn 1 and the varying pattern of spacer yarn 2. The patterns and relevant set ups for the components of the samples examined are given in *Tables 2* and *3*. The spacing of the warp and wefts inserted yarns is 8 mm.

Table 1. Properties of spacer fabric components (X - Not used, N/A - Not applicable).

Component	Description	Elastic behaviour	E, N/mm²	v	B, N·mm²	σ yield stress, N/mm²
warp knitting yarn	16 tex multifilament PP	X	X	X	X	X
0° yarn	2400 tex AR-Glass Roving	Linear elastic	72000	0.3	24	N/A
90° yarn	2400 tex AR-Glass Roving cabled with PA twisted yarn	Linear elastic	72000	0.3	24	N/A
spacer yarn 1	0.25 mm PES monofilament (white)	Bilinear elastic	E1 = 4876 E2 = 2252	0.3	0.94	167.2
spacer yarn 2	0.30 mm PES monofilament (black)	Bilinear elastic	E1 = 5141 E2 = 1792	0.3	2.04	151.7

Table 2. The patterns and relevant setups for warp knitting yarns, 0° and 90° yarn and spacer yarn 1.

Component	Number of the needles used	Threading	Pattern
0° yarn	42	1 full 1 empty	0000/1111
90° yarn	42	1 full 1 empty	Weft
Warp knitting yarn	42	1 full 1 empty	0101//
Spacer yarn 1	42	1 full 1 empty	0110//

Table 3. The patterns and relevant setups for the spacer yarn 2.

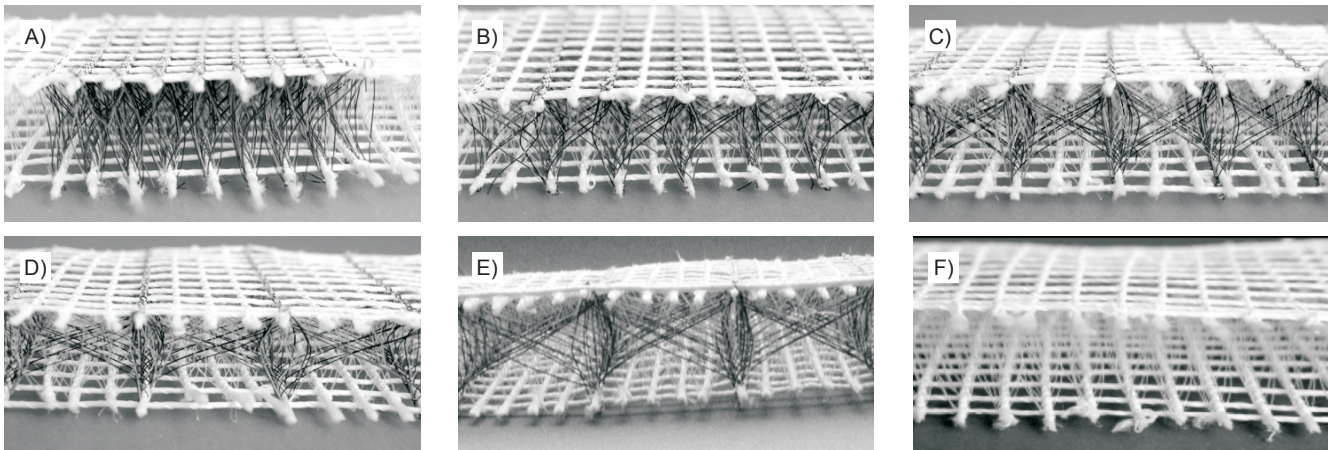| Component	Sample	Threading	Pattern
Spacer yarn 2	A	1 full 1 empty	1 2 3 4 / 4 3 2 1
	B	1 full 3 empty	1 2 5 6 / 6 5 2 1
	C	1 full 5 empty	1 2 7 8 / 8 7 2 1
	D	1 full 7 empty	1 2 9 10 / 10 9 2 1
	E	1 full 9 empty	1 2 11 12 / 12 11 2 1
	F	-	-

***Figure 2.** Group of samples of warp-knitted spacer fabrics.*

The initial thickness of the spacer fabrics was 25 mm. Cross-sectional pictures of the samples are presented in ***Figure 2***.

Experimental data

The Young modulus of the yarns was measured using TEXTECHNO Testing Apparatus. The sample length was 250 mm, the test speed 250 mm/min, and the pretension 50 N/tex. However, the bending rigidity of the single filaments was calculated based on beam mechanics. Since the structural elements were synthetic filaments, they could easily be considered as beams of a cylindrical structure. The bending rigidity of the glass roving cabled with PA twisted yarn was measured using a respective test. The compression test of the samples was performed on Zwick/Roell 2.5 testing equipment. The procedure for the compression test of the spacer fabrics was defined, since there was not a related standard in use available [8, 9]. According to this, a pressure stamp of 50 mm diameter is mounted on the device. Samples were cut in a circular area of about 200 mm diameter. The test speed was set at 100 mm/min. The testing device measured the forces developed for the com-

pression displacements applied. The experimental data are used for evaluation of the accuracy of the modelling method proposed.

Modelling and simulation

Two scales of modelling are adopted for simulation of the compression test of the spacer fabric. The Finite Element Method is implemented in each modelling stage, applying the beam, solid and shell theory depending on the simulation requirements. The first scale corresponds to the micromechanical analysis of the spacer and outer layers individually in which the apparent mechanical properties are defined. Thereafter the apparent properties? are introduced in the macromechanical model of the total sample developed in the second stage for simulation of the compression test. The principle of the methodology proposed is the replacement of the discrete structure of each layer with a continuum structure presenting an identical mechanical performance. The replacement of the discrete models with continuum layers is signally beneficial for a reduction in the computational cost. Thus simulation of the compression

test of the total sample was possible in an acceptable time period.

Micromechanical modelling of the spacer layer

The micromechanical modelling of the spacer layer is conducted to predict and evaluate the mechanical properties of the spacer layer with respect to the layer structure and properties of the constituting spacer yarns (***Table 1***). The structural complexity of the spacer layer demands the generation of a short part of the structured considered for a reduction in the computational cost. Thus modelling of the layer's unit cell was undertaken. Since the compression test of the total sample induces compression in the spacer layer, the compression resistance was principally studied. Although the unit cell of the spacer layer is adequate for the current stage of modelling, the adjacent yarns of the outer layers are also presented in the model generated for precise representation of the structure. Two basic assumptions are introduced for representation of the spacer yarns. Firstly, the spacer yarns are considered bonded at the warp yarns of the outer layers. The effect of the omitted loops of the spacer filaments (around the 0º yarns of the outer layers) and omitted warp knitted yarn is assured by implementing the appropriate constraint equations. The spacer filaments are represented as fixed on the outer layers, since the loops of the spacer filaments are constantly connected to the outer layers (by the warp knitting yarn). Secondly, the length of the spacer yarns is assumed equal to the one obtained with respect to their straight formulation in the initial spacer fabric thickness. Therefore the length of the straight parts (spacer yarns) connecting the outer layers for a distance of 25 mm (distance of the two
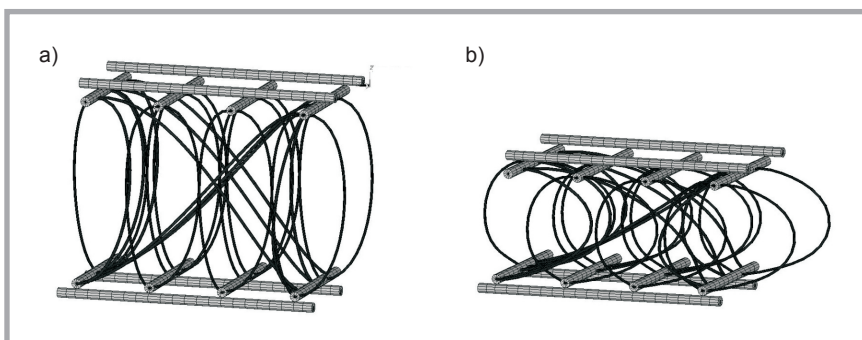

***Figure 3.** Discrete model of the unit cell (sample C) in an undeformed (a) and deformed state (b).*

needle bars) is calculated. The removal of the fabric from the knitting machine incurs a reduction in the distance of the outer layers (≈20 mm) and the curved form of the spacer yarns. According to the technique proposed, spacer yarns are represented by selected spline curves connecting the binding points, which present the length calculated [10, 11].

The FEM using beam elements is implemented for simulation of the model compression. The beam theory is considered an appropriate method for the analysis, given that the yarn bending constitutes the dominant deformation of the compression of the spacer layer. For simulation of the compression of the unit cell, the lower outer surface is simply supported while the upper surface moves vertically, reducing the distance between them. The rotations of the nodes at the connection points are also restricted (around the warp and weft directions) in order that penetration of the outer layers by the spacer yarns be prevented. A full Newton-Raphson algorithm supporting
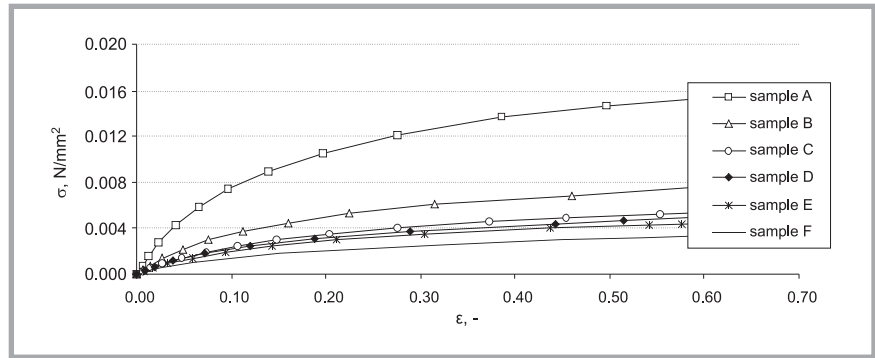

Figure 4. Stress – strain curves from simulation of the compression test of the spacer layer.

large strain effects is implemented for the nonlinear solution procedure. The undeformed and deformed models of the unit cell (for sample C) are presented in *Figure 3* (see page 58). The reaction developed by the applied displacement is derived. The load – displacement curve resulting from the simulation is converted to the stress (load/area) – strain (displacement/initial thickness) curve, considering the apparent unit cell area. Therefore the compression resistance of the unit cell is reflected in the value of the elastic modulus for the continuum model of the spacer layer. Stress – strain curves corresponding to the six samples are given in *Figure 4*. Thus a multilinear curve describes the elasticity of the spacer layer in each case.

Micromechanical modelling of the outer layer

Micromechanical modelling of the outer layer is applied for evaluation of the mechanical properties of the outer surfaces with respect to the structural and mechan-
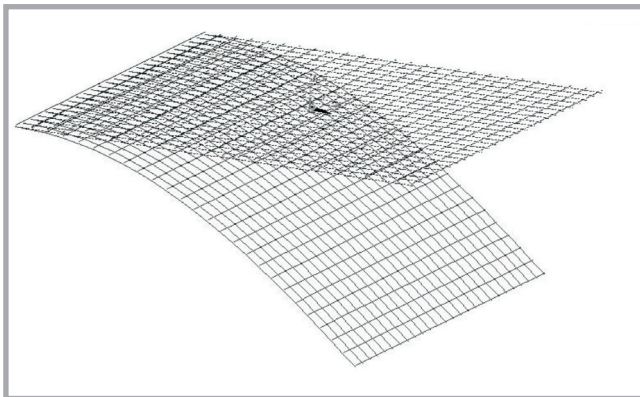

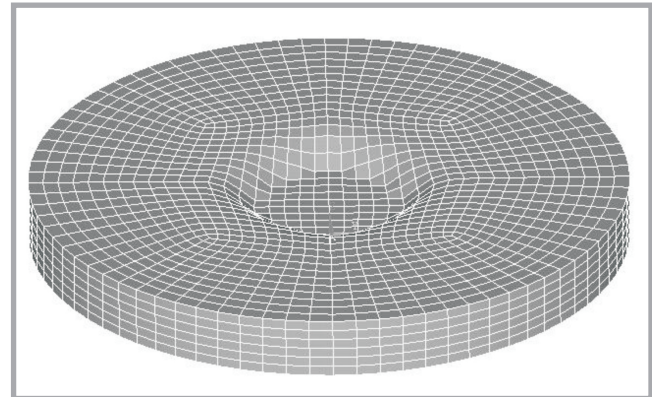*Figure 5. Bending deformation of the outer layer model*
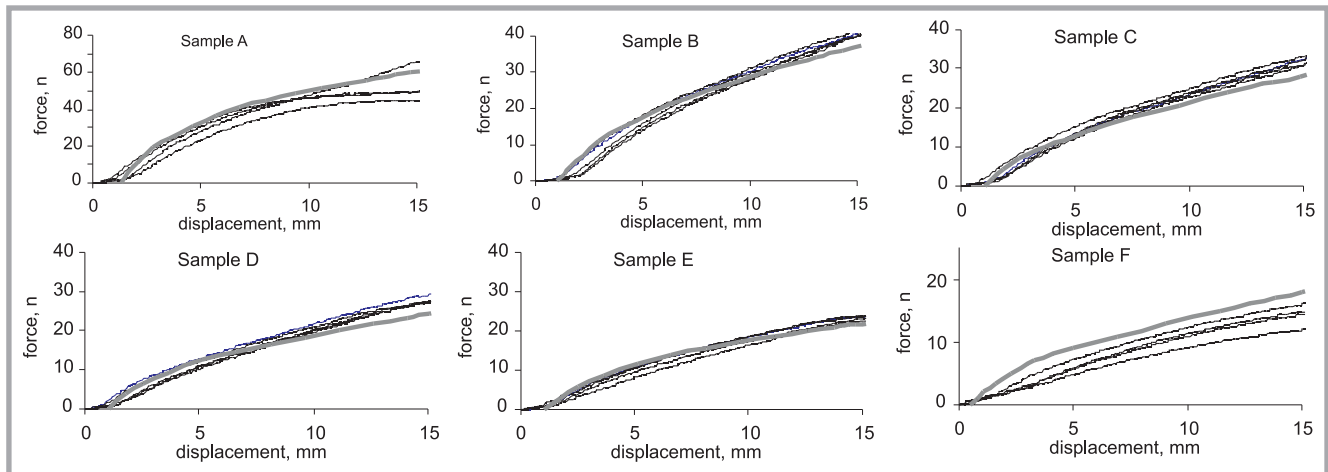

Figure 6. Deformed macromechanical model.

Figure 7. Load – displacement curves resulting from the compression test of the group of samples from the experiment (black) and simulation (grey).
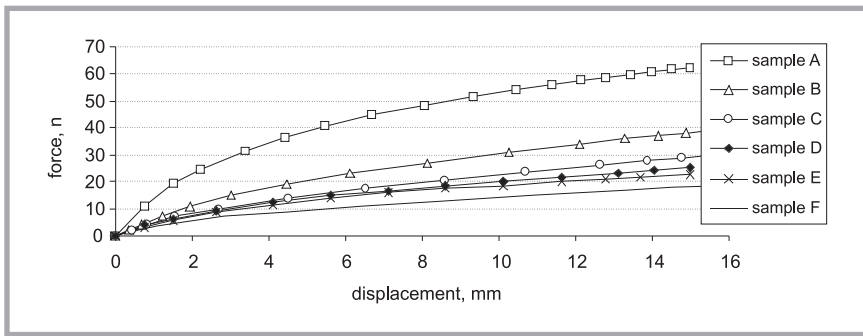
Figure 8. Predicted load – displacement curves resulting from the compression test of the group of samples.

ical properties of the constituting yarns. The compression test of the total sample incurs complex deformation of the outer surfaces, including bending. Thus the bending rigidity and elastic modulus are required for the replacement of the discrete by a continuum model. FEM using beam elements is implemented for the micromechanical analysis of the structure. Equal displacements are imposed for the nodes corresponding to the cross-points of warp-wefts in order that the lacing of the yarns is described. The deformed model resulting from bending is presented in *Figure 5*. Linear analysis is applied for the tensile deformation. Nonlinear analysis, in contrast, is implemented for the bending deformation. An apparent thickness is defined for calculation of the apparent elastic properties. Thus equivalent values resulted from the simulation: thickness = 0.0671 mm, elastic modulus = 124031 N/mm² and bending rigidity = 624 N·mm² .

Macromechanical modelling of the total sample

Thereafter the apparent partial properties of the outer and spacer layers derived are introduced in the macromechanical model of the total sample for simulation of the complex deformation during the compression test. The macromechanical model consists of an internal volume and two overlaid surfaces corresponding to the spacer and outer layers, respectively. The volume is meshed by solid elements while shell elements are laid on the surfaces. The volume thickness is defined equal to the thickness of the spacer layer. Multilinear isotropic elasticity is considered for the internal volume. Stress-strain curves of the continuum material correspond to the ones given in *Figure 4*. Linear orthotropic properties are introduced for the surface material. The shell thickness and elastic modulus of the continuum surface model, given above,

describe the tensile and bending behaviour of the discrete model. The boundary conditions applied for simulation of the compression test of the total sample correspond to the simple support of the lower outer surface and load of the upper outer surface. For application of the load, a node component is selected in the area corresponding to the stamp surface, constrained with equal vertical movement. A nonlinear solution is implemented for the analysis. The deformed model is presented in *Figure 6*. Load – displacement curves resulting from the simulation of the compression test for the group of samples are given in *Figure 7* with corresponding experimental curves.

■ Results and discussion

The satisfactory coincidence of the predicted and experimental load – displacement curves of the compression test (*Figure 7*) ensures the reliability of the computational modelling method proposed. Thereafter the method proposed is implemented for analysis of the effect of certain structural and physical parameters of the spacer fabric in its compression performance. The pattern of spacer yarn 2, such as the mechanical properties of the yarns, constituting the spacer and outer layers, are considered substantial for the compression resistance of the specific type of spacer fabric. Actually, the effect of the pattern of spacer yarn 2 arises from the comparison of the load – displacement curves of the samples studied (A, B, C, D, E, F). The curves are
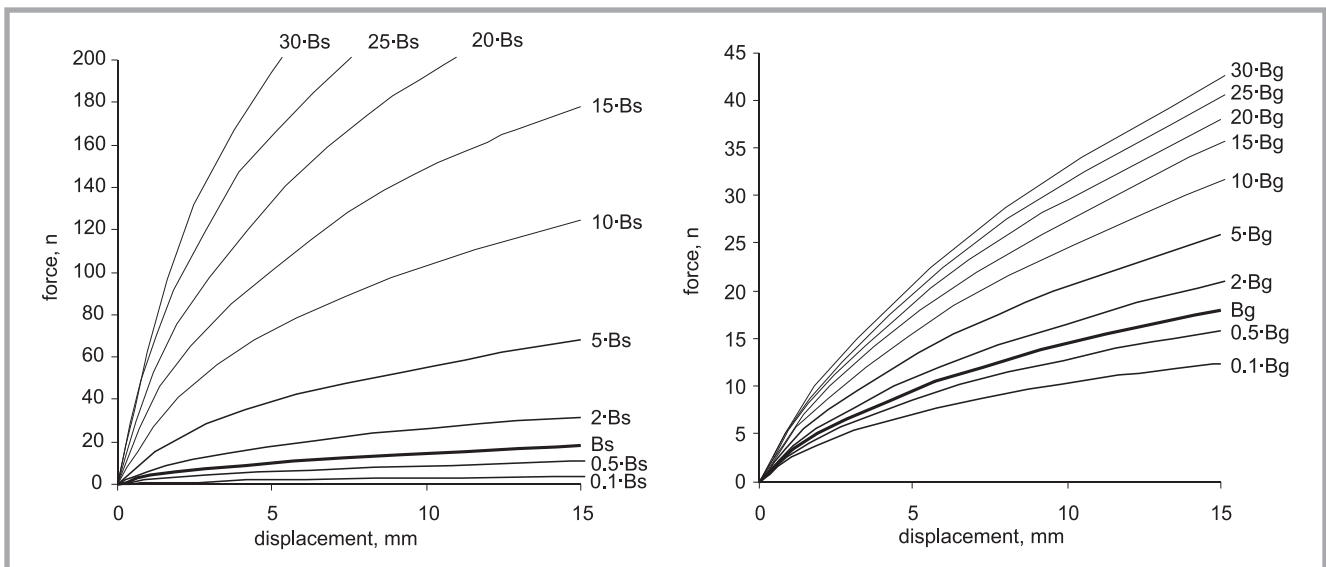

Figure 9. Predicted load – displacement curves resulting from the simulated compression test of sample F with varying values of the yarn bending rigidity for the spacer layer (left) and outer layer (right).
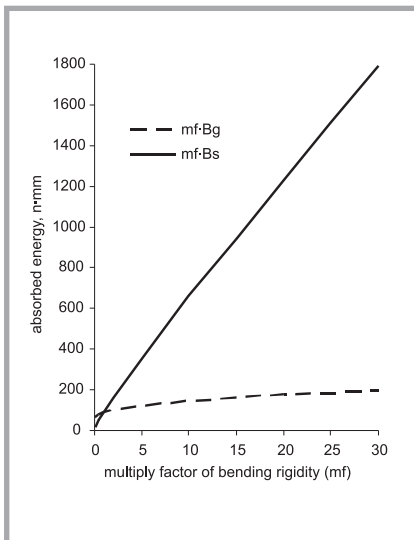
Figure 10. *Effect of the bending rigidity of the yarns on the energy absorbed for a compressive deflection of 10 mm.*

presented in ***Figure 8***. The loose knitting of spacer yarn 2 obviously leads to lower compression resistance. The divergence of the compression resistance between patterns A and B is remarkable. Moreover, the samples with patterns C, D, E present approximately the same compression performance. Sample F corresponds to the structure produced without spacer yarn 2.

The effect of the mechanical properties of the yarns constituting the spacer and outer layers in the compression performance of the spacer fabric is investigated. The structure of sample F is considered as representative of the analysis. Linear elastic properties are assumed for the yarns as well. Given the domination of the yarns' bending phenomenon in the deformation procedure during the compression test, the bending rigidity range of the yarns must be defined for the analysis. Thus ten values of bending rigidity are considered for the glass yarns ($Bg = 24$ N·mm², $0.1·Bg$, $0.5·Bg$, $2·Bg$, $5·Bg$, $10·Bg$, $15·Bg$, $20·Bg$, $25·Bg$, $30·Bg$) and spacer yarn 1 ($Bs = 0.94$ N·mm², $0.1·Bs$, $0.5·Bs$, $2·Bs$, $5·Bs$, $10·Bs$, $15·Bs$, $20·Bs$, $25·Bs$, $30·Bs$). Modification of the bending rigidity of the yarn can be achieved by changing the Modulus of elasticity or the moment of inertia of the cross section. Both cases incur an identical performance for the constituted layer. Thus two groups of samples were modelled for the analysis: the first corresponds to a constant value of the glass yarn's bending rigidity (Bg) and a varying value of the spacer yarn's

rigidity, while the second corresponds to a constant value of the spacer yarn's bending rigidity (Bs) and a varying value of the glass yarn's rigidity. The load – displacement curves from the simulation of the compression test of the two groups are presented in ***Figure 9***. The load – displacement curves of ***Figure 9*** support the qualitative assessment of the effect of the bending rigidity of the yarns constituting the spacer and outer layers. The increase in the compression resistance of the sample due to the increase in the yarn's bending rigidity is obvious. Comparing the graphs, the impact of the bending rigidity of the spacer yarns also increases . The curve of the model developed for the basic values of Bg and Bs is presented as the bold line. For quantitative comparison of the impact of spacer and glass yarns on the sample compression performance, the energy absorbed for a standard compressive deflection (10 mm) is calculated. The energy absorbed corresponds to the area formed between the load – displacement curve and the displacement axis up to the selected value of displacement (10 mm). The energy absorbed, depending on the bending rigidity of the yarns, is given in ***Figure 10***. Consequently, the multiplication by ten of the bending rigidity of the spacer yarn incurs an increase in the absorbed energy of 6 – 7.6 times, while the same increase in the bending rigidity of the glass yarns incurs an increase in the absorbed energy of 1.3 – 1.7 times.

■ Conclusions

A simulation method was developed for the prediction of the compression performance of spacer fabrics for concrete applications. The method proposed comprises two stages of mechanical analysis at micro- and macroscopic levels. Finite Element Analysis, the applying beam, solid and shell theory, was implemented at each modelling stage. Micromechanical analysis was conducted separately in the spacer and outer layers of the fabric for evaluation of their performance in compression and bending, respectively. The results were used for calculation of the apparent properties of the continuum models. The principle of the methodology proposed was the replacement of the discrete structure of each layer by a continuum structure presenting an identical mechanical performance.

The accuracy of the method proposed was evaluated with experimental data for a group of six samples. Adequate fitting between the experimental and predicted curves of load – displacement assures the reliability of the method used . Moreover, the effect of the varying pattern of spacer yarn 2 on the compression performance of spacer fabric was thoroughly investigated. Finally, the effect of the bending rigidity of yarns constituting the spacer and outer layers was examined in order to complete the analysis of the structural parameters influencing the behaviour of spacer fabrics.

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