**Moniruddoza Ashir*, Cornelia Sennewald, Gerald Hoffmann, Chokri Cherif**

**Institute of Textile Machinery and High Performance Material Technology, Technische Universität Dresden,**
01069 Dresden, Germany
* E-Mail: Moniruddoza.ashir@tu-dresden.de

# Development of Woven Spacer Fabrics Based on Steel Wires and Carbon Rovings

**DOI:** 10.5604/12303666.1227882

**Abstract**
*Woven spacer fabrics are used as reinforcing materials for fiber-reinforced plastics. These fabrics consist of mostly pliable textile fibers, which still require defined rigidity for different crash applications. In this regard, multi-material woven spacer fabrics present a promising approach. This paper presents the development of multi-material woven spacer fabrics using steel wire and carbon rovings. For the development of such woven spacer fabrics, a systematic structure realization based on the weave pattern was performed. Selected structures were produced on a modified weaving machine.*

**Key words:** *multi-material woven spacer fabrics, structure realization, profiled wire, pull-out test.*

## Introduction

In recent years, research on spacer fabrics as a reinforcement structure for fiber reinforced plastics (FRP) application has become increasingly popular because of the better mechanical properties on offer such as tensile, flexural and compression strength when compared to other materials for lightweight constructions such as aluminum or magnesium, which makes them highly suited as panel structures for aeroplane, train or automotive body construction [1]. Spacer fabrics are a class of three-dimensional fabrics where two surface layers are connected to each other by means of pile yarns or fabric layers [2]. Such fabrics are characterized by better resilience properties than classical two-dimensional textile fabrics [3]. Typically spacer fabrics used for FRP application are made of high-performance fibers, such as carbon, glass or aramid fibers characterized by lower density as well as a higher tensile strength and Young´s Modulus [4].

Studies on spacer fabrics show a variety of approaches for their production, characterisation and varied application possibilities. Spacer fabrics for technical applications are commonly produced by the circular knitting process (weft-knitted spacer fabrics), double needle bar warp knitting process (warp-knitted spacer fabrics) or weaving process (woven spacer fabrics) [5-7]. However, woven spacer fabrics exhibit superior mechanical properties, for instance higher stiffness, strength and dimensional stability, than those of knitted spacer fabrics [8]. Woven spacer fabrics typically consist of two sets of warp and weft yarns each. These yarn systems are used for the fabrication of two layers of spacer fabrics (upper and lower layer) and the warp yarns interchange their position after a certain interval to make a fabric layer in the vertical direction between them.

In previous works executed at the Institute of Textile Machinery and High performance Material Technology at Technische Universität Dresden, machine and process optimization, the development of woven spacer fabrics and their comprehensive characterization were carried out. Very few publications on woven spacer fabrics for lightweight applications are readily available in literature [8-12]. One of the first examples of woven spacer fabrics was presented in [9]. Here the development of a weaving machine for the production of spacer fabrics for FRP is described. These fabrics consist of polyester and viscose yarns. Mountasir et al. [8] exclusively investigated the mechanical properties of woven spacer fabrics. The spacer fabrics developed are composed of glass-polypropylene hybrid yarns. Similar to woven spacer fabrics, 3D woven wire structures have also been studied [13-17]. The development of 3D woven wire structures of a cellular design for multifunctional multi component-composite semi-finished products is reported in [13]. However, this paper presents a fundamental approach that aims to provide a novel fundamental technological basis for the production and characterization of such structures. This paper is organised into 3 sections, where the structure development is presented in the **Theoretical structural realization for the development of multi-material woven spacer fabrics (MWSF)** section, the implementation of structures – in the **Technology development** section, and fabrics developed are analysed in the **Results and discussion** section.

## Theoretical structural realization for the development of MWSF

The MWSF proposed also consists of two fabric layers, in which the top and bottom are similar to conventional woven spacer fabrics. These layers are connected

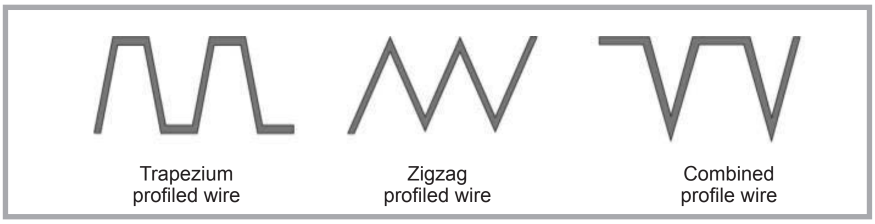


***Figure 1.** Different profiled wires for realization of the MWSF structure.*

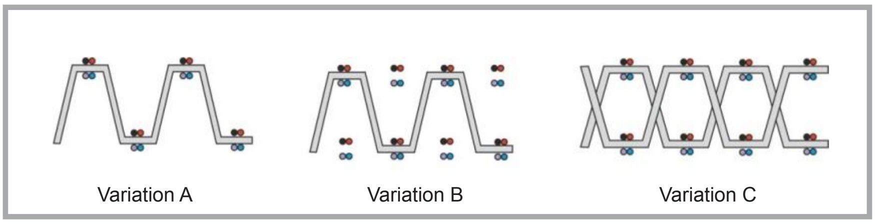


***Figure 2.** Structural variation possibilities based on the arrangement of profiled wires and the number of warp yarns.*

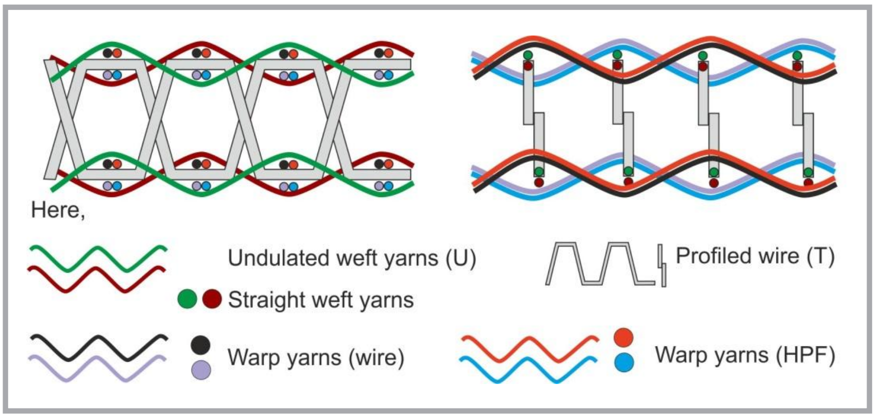


***Figure 3.** Example of MWSF structures proposed – left: front view, right: side view (HPF = High-performance fibers).*

together by profiled wires as opposed to pile yarns or fabric layers, which are used in conventional woven spacer fabrics.

### Structural variation possibilities

Theoretical structural variation possibilities for the development of MWSF can be realised by the interlacement of yarns, profiled wire geometry, direction of insertion of the profiled wire in between the top and bottom layer of fabrics, the number of yarns per repeat and the undulation of weft yarns.

The interlacement variation of warp yarns, weft yarns and profiled wires in MWSF structures can be implemented by plain, twill or satin weave patterns. The structural deformation, slippage resistance, yarn pull-out force, bending resistance and handling stability of plain woven fabric is better than that of twill or satin fabrics [18]. For this reason, the plain weave pattern is taken into consideration for further structural realization of MWSF.

Profiled wire geometry variations such as trapezium (flat top surface), zigzag (pointed top surface) or combined (combination of a flat and pointed top surface) profiled wire (c.f. ***Figure 1***), can be used. In this work, however, only zigzag and trapezium profiled wire were considered in order to reveal the effect of the profiled wire geometry (flat or pointed top surface) on the sliding resistance of warp yarns, which in turn determines the structure stability.

Further structural variation of MWSF structures can be realized considering the direction of profiled wire insertion in between the upper and lower layer of MWSF during weaving. Profiled wire can be inserted in either warp or weft as well in both directions. For the realization of MWSF structures, profiled wire insertions between two layers of MWSF are considered only in the weft direction, so that the geometrical shape of the profiled wire can be retained during picking.

Different MWSF structures can also be realized by varying the arrangement of the profiled wire and the number of warp yarns in a repeat. Different variation possibilities in this aspect are as follows:

- All profiled wires in a MWSF structure can be arranged in an identical manner and warp yarns can be interlaced with weft yarns as well as profile structures at the peak of the profiled structure – (A),
- All profiled wires in a MWSF structure can be arranged in an identical manner and warp yarns can be interlaced with weft yarns as well as profile structures at the peak of the profiled wire in addition to the space between two peaks of the profiled wire – (B). In this variation, the warp yarn density is twice that of variation (A).
- Two profiled wires are placed face-to-face but turned upside down in a repeat, and warp yarns are interlaced with weft yarns and profiled wire at the peak of the profiled wire – (C). Here, the profiled wire density is twice that of variations (A) and (B).

Variations (A), (B) and (C) are shown in ***Figure 2***, where dots indicate warp yarns.

Depending on the undulation of weft yarns during interlacement with the warp, two variations of MWSF structures can also be realised:

- MWSF structures with undulated weft yarns – (U) or
- MWSF structures with straight weft yarns – (S).

### Sample construction of structure proposed

A proposed MWSF structure is shown in ***Figure 3***. This is a representative sample of the structure realized in ***Figure 4***.

In ***Figure 3***, MWSF structure is formed of an upper and lower layer of fabrics with a trapezium profiled wire – (T) in between them. This trapezium profile wire is inserted in the weft direction between the upper and lower layer of fabrics. The profiled wire, weft, and one set of warps in the upper and lower layer of fabric are made of wire. Another set of warps is made of high-performance fibers. Two trapezium profiled wires are placed face to face but turned upside down, and warp yarns are interlaced with both profile wires and weft yarns at the peak of the profiled wire – (C). The weft yarns are undulated and interlaced with warp yarns – (U). From these three points, MWSF structure shown in ***Figure 3*** is concluded as TCU.

**Realization of possible structures**

From the variation possibilities described above and the corresponding MWSF development point of view, overall 12 types of MWSF structures were realized in this work. For each profiled wire type of trapezium (T) and zigzag (Z) developed, 6 types of MWSF structure were designed. MWSF structures realized by means of their coding are represented in ***Table 1***.

Since the warp and weft yarns in the upper and lower layers of the MWSF structures realized are interlaced in a plain weave pattern, only two sequences are necessary to represent their interlacement. MWSF structures based on trapezium profile wires, including their first and second sequence of interlacement, are demonstrated in ***Figure 4***. In the structures developed, the warp yarn combination consists of both wire as well as high performance fibers. The material for the weft and profile structure is wire. Each MWSF structure comprises 2 sets of warp yarn combination, 2 sets of weft yarns and 1 set of profiled wire.

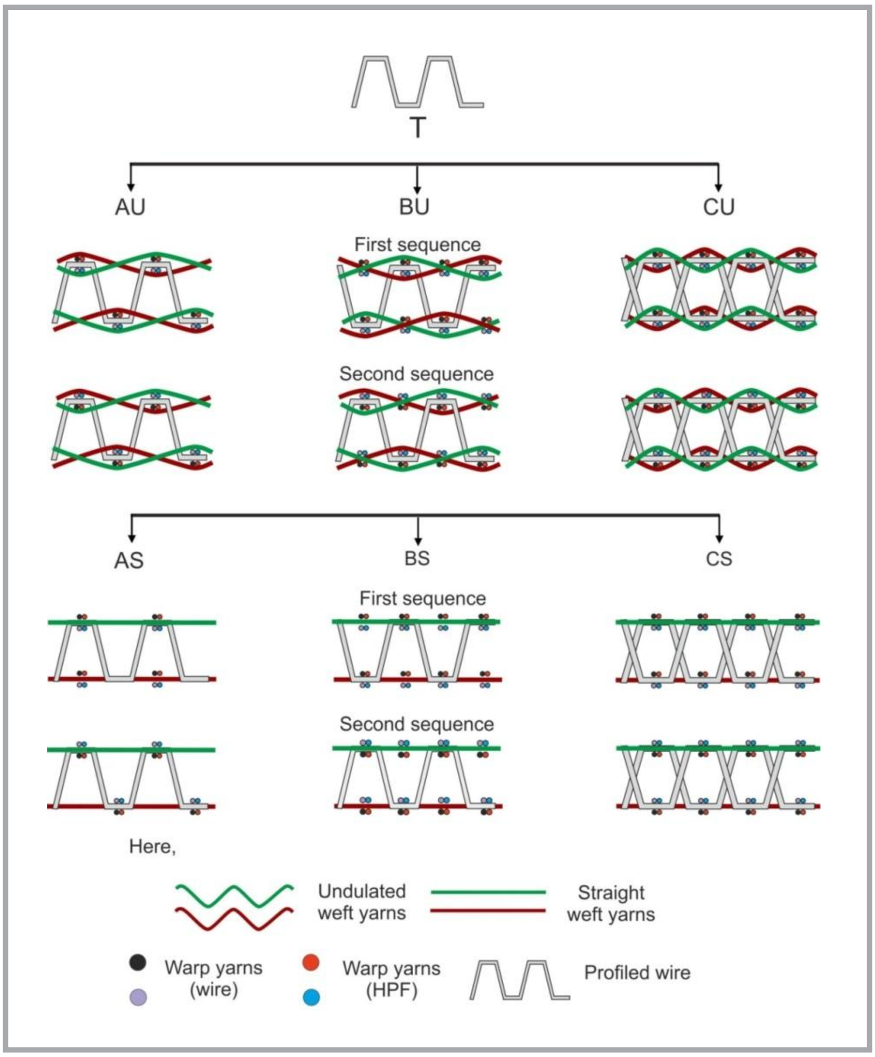


***Figure 4.*** *MWSF structures consisting of a trapezium profile in between the upper and lower layer of fabrics (here, HPF = High-performance fibers).*

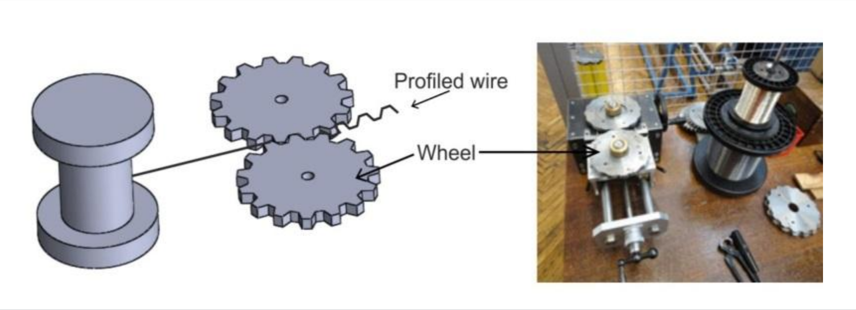


***Figure 5.*** *Schematic diagram (left) of the crimping machine with actual set up (right).*

***Table 1.*** *MWSF structures realized.*

| Profiled wire geometry | Undulation | Type | Designation |
|---|---|---|---|
| T / Z | U | A | TAU / ZAU |
| | | B | TBU / ZBU |
| | | C | TCU / ZCU |
| | S | A | TAS / ZAS |
| | | B | TBS / ZBS |
| | | C | TCS / ZCS |

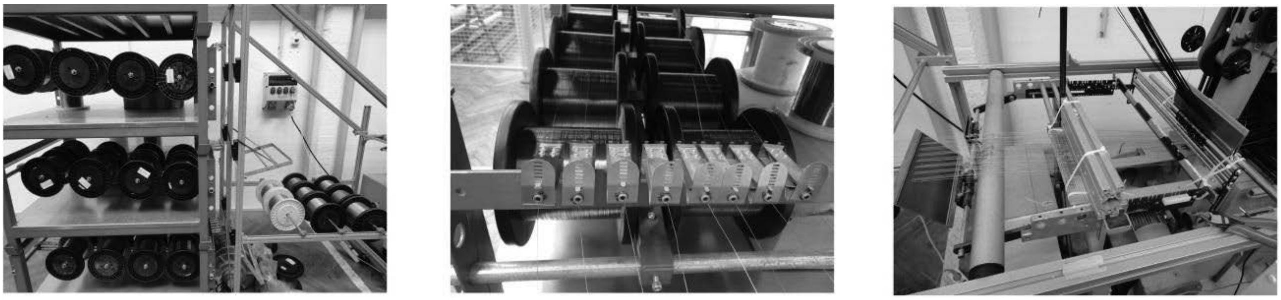
## Technology development

**Materials**

For the first approach to develop MWSF, the steel wire- carbon roving combination was used in this study for the development of MWSF. The diameter, tensile strength and density of the steel wire selected (Harald Uhlig Stahldraht GmbH, Germany) for the fabric development proposed were 0.4 mm, 752 N/mm$^2$ and 7.85 g/cm$^3$, respectively [19]. The fineness, tensile strength, elongation and density of the carbon roving used (Toho Tenax Europe GmbH, Germany) were 400 tex, 4400 MPa, 1.8% and 1.77 g/cm$^3$, respectively [20].

**Production of profiled wire**

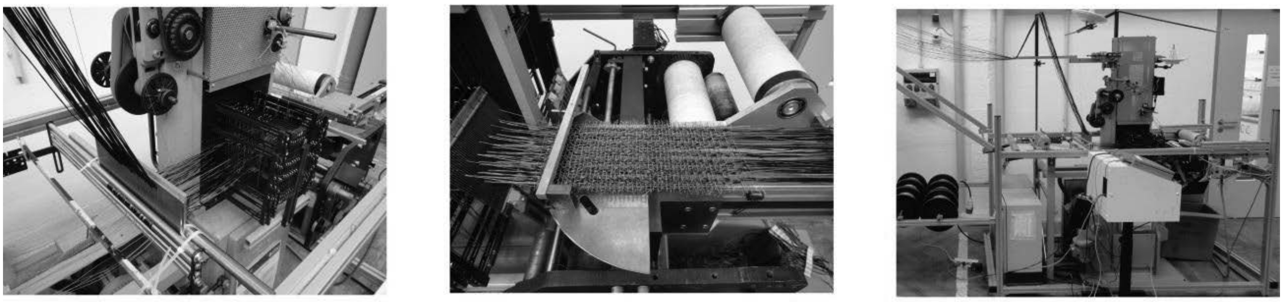
For the production of profiled wire for connecting the upper and lower lay-



Warp creeling system

Warp tensioning system

Warp path over the reed



Shedding unit

Take-up unit

Overall machine set-up

***Figure 6.*** *Constructive arrangement of a needle ribbon weaving machine for the development of MWSF.*

er of the MWSF proposed, a crimping machine was employed. This machine is composed of two gear wheels, a handle to operate the wheels and an adjusting handle to control the space between them. Steel wire from the spool is introduced into the two wheels of the crimping machine, and during the rotation of the handle, profiled steel wire is produced. A schematic diagram and actual set up of the crimping machine employed are illustrated in ***Figure 5*** (see page 51).

The shape of the profiled wire depends on the shape of the gear wheel of the crimping machine. Specifications of the profiled structure produced for this study on this crimping machine are listed in ***Table 2***.

***Table 2.*** *Specification of the profiled wire produced.*

| Parameter | Profiled wire type | Value, mm |
|---|---|---|
| Height of profiled wire | Trapezium | 11 |
| | Zigzag | 10 |
| Distance between two adjacent peaks | Trapezium | 28 |
| | Zigzag | 14 |

***Table 3.*** *Dimensional parameters of MWSF developed.*

| MWSF type | Height, mm | Width, mm | Length, mm |
|---|---|---|---|
| TCU | 11 | 100 | 250 |
| TCS | 11 | 100 | 250 |
| ZCU | 10 | 50 | 250 |
| ZCS | 10 | 50 | 250 |

### Modified weaving machine

A modified needle ribbon weaving machine (NFREQ42/2/130-3N, Maschinenfabric Jakob Müller AG, Frick, Switzerland) was employed for the production of MWSF. This is a semi-automated weaving machine featuring a dobby shedding mechanism. The retention mechanism of warp yarns are electronically controlled by the weave data program. The maximum width of the fabric produced on this weaving machine is 130 mm. All the primary functions as well as secondary functions of weaving are controlled by a servo motor. The total number of heald frames in this machine is 20. The modified needle ribbon weaving machine was fitted with a guide element to prevent the projecting out of warp wires from the fabric, as well as with a linear take-up unit as opposed to a rotating unit so as to prevent any damage to the three-dimensional structures produced. The motion of the linear take-up unit is controlled by a stepper motor. The consecutive arrangements of the needle ribbon weaving machine are demonstrated in ***Figure 6***. The detailed machine technology of this modified loom can be found elsewhere [14].

### Development of MWSF

All the 12 types of MWSF structures realized were developed in preliminary weaving trials. However, based on their handling stability, four types of MWSF (TCU, TCS, ZCU and ZCS) are further described in this paper. Considering the machine construction, spools instead of a weaver's beam were used for the development of MWSF. Here warp yarns of steel wires and carbon rovings were let-off from different spools during weaving. The steel wire and carbon roving spools are placed on the creel. Warp yarns are drawn by the negative let-off motion, where the tension on warp yarns imparts the driving force against friction forces. Structures are realized on the weaving machine by the proper designing of

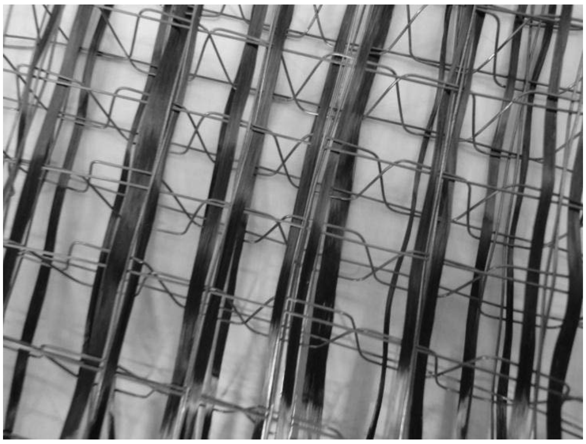


*Figure 7. Exemplary representation of MWSF developed (TCS).*

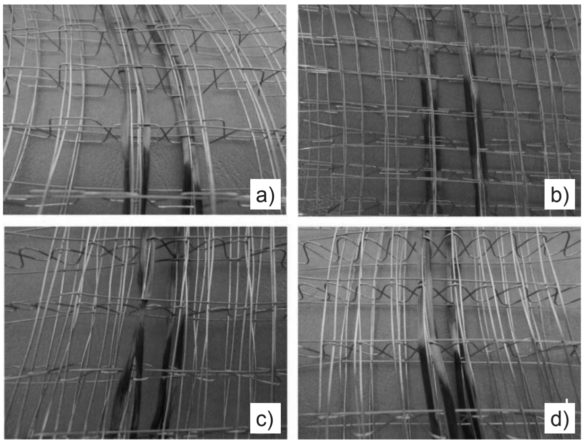


*Figure 8. Multi-material woven spacer fabrics a) TCU, b) TCS, c) ZCU, d) ZCS.*

a weaving plan. From the weaving plan, for the development of MWSF, the repeat (8x8) and drafting system (plain draft) are derived. 8 heald shafts are employed during the development of MWSF, where the steel wire and carbon rovings are lifted in pairs. The insertion of the profiled wire in between two layers of fabric is executed in the shedding mechanism. As the machine used is semi-automated, the picking for both weft yarns and profiles wires are executed separately by hand. Among the three fixed take-up speeds in the weaving machine – high (38 mm/s), middle (28 mm/s) and low (18 mm/s), the low speed is chosen for the preliminary test because of the high tension of the wire between the creel and the clamp of linear take-up. The linear take-up distance of the loom is set to 15 mm. By this set distance, the linear take-up unit moves forward after inserting weft yarns and profiled wires in a repeat, corresponding to their beat-up. After reaching the length of MWSF required, it is cut by pliers and stored in a planar form. Besides the linear take-up motion, the shape of MWSF is retained by inserting two wood pieces equal to the profiled wire height in between the two layers of MWSF on both sides of the fabrics in the warp-direction. The MWSF with three-dimensional parameters developed are listed in ***Table 3***.

### Testing

In order to investigate the effect of the flat and pointed top surface of the profile structure on the sliding resistance of warp yarns with weft yarns and profiled wires, the interaction between different types of materials and to obtain structure stability for the subsequent process, a pull out test was conducted. A tensile testing machine (Zwick Z2.5, Germany) was used for this purpose. No specific standard is currently available to carry out this test. In this testing, one end of the test specimen is clamped by the lower clamp of the tensile tester. From another end, only one yarn to be tested is clamped by the upper clamp of the tensile tester. Then the warp yarn is cut at the bottom and is pulled out from MWSF at a constant speed of 20 mm/s until the set length and the corresponding force to pull out a yarn from the fabric is measured. For each sample, this test is repeated seven times. The parameters under which this test is carried out are stated in ***Table 4***.

## Results and discussion

### Visual evaluation of samples produced

An exemplary representation of the MWSF developed (TCS) is illustrated in ***Figure 7***.

In order to accentuate the interlacement among yarns, all carbon rovings, except one adjacent pair, from both the top and bottom fabric layer of MWSF are removed. The MWSF developed are represented in ***Figure 8***, where the two MWSF's in the first row of ***Figure 8*** (***a*** and ***b***) consist of trapezium profiled wire, and the last two samples in second row (***c*** and ***d***) are MWSF based on zigzag profiled wire. The first and second column of the images represent the undulated and straight weft yarns.

The warp yarn density of MWSF made of zigzag profiled wire is twice than the trapezium because the adjacent peak distance of the zigzag profile is half of that of trapezium profiled wire. Due to the flat top surface of the trapezium profiled wire, the warp yarns remain in the middle of the profiled wire. On the contrary, the warp yarns of the zigzag profile do not remain in the middle position of the wire; however, the carbon roving remains in the top position. Comparing the structures composed of trapezium and zigzag profiled wire, the handling stability of MWSF made up of zigzag profiled wires is inferior to that of trapezium profiled wire due to their geometrical shape.

### Evaluation of sliding resistance

***Figure 9*** (see page 54) depicts the force-distance curve for four different types of MWSF (TCU, TCS, ZCU, ZCS) resulting from the pull-out test. In this graph, sample representations of pull-out curves of warp yarns made of steel wire are shown.

In the course of testing, the number of weft yarns and profiled wire rubbing against the warp yarn being pulled out is reduced, hence after an initial peak, less force is required to pull out warp yarns. It is specifically noticeable that all curves in ***Figure 9*** jump after a certain

***Table 4.*** *Parameters to carry out the pull-out test*

| | |
|---|---|
| Test speed, mm/s | 20 |
| Clamping distance, mm | 100 |
| Initial force, N | 1 |
| Load sensor, kN | 2.5 |
| Travel sensor | Traverse |

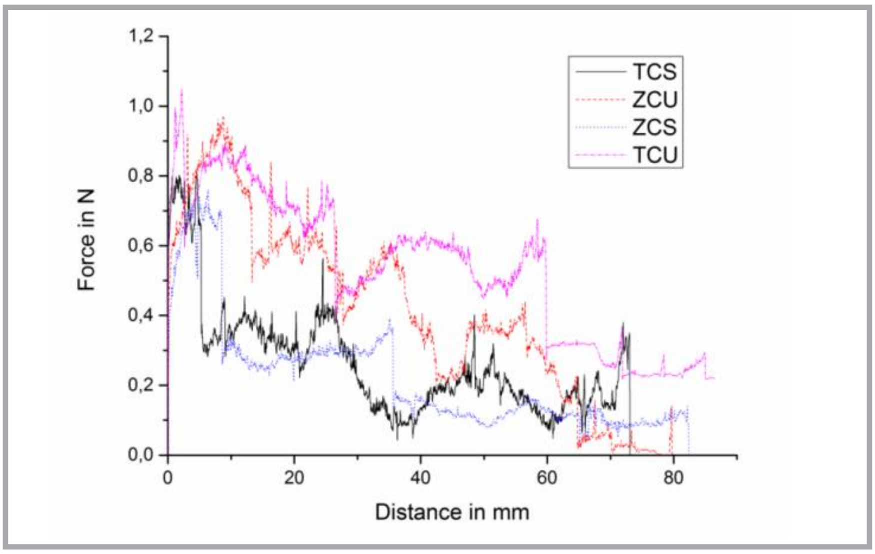


***Figure 9.*** *Force-distance curve of warp yarns during the pull-out test.*

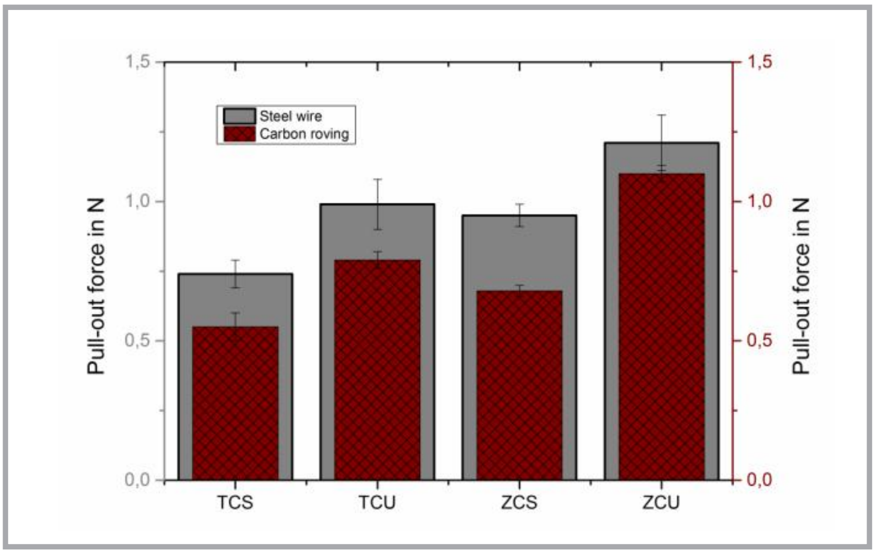


***Figure 10.*** *Pull out test of wire and carbon roving from MWSF.*

interval, which is due to the linear take-up distance among the set of weft yarns and profiled wires. The average pull out force along with the standard deviation of the steel wire and carbon roving from MWSF is demonstrated in ***Figure 10***.

From ***Figure 10***, it can be concluded that the pull-out force of the steel wire and carbon rovings in structures consisting of zigzag profiled wire is higher in comparison to the trapezium profiled wire because of the pointed top surface of the latter. The pull out force of the warp yarns from the undulated structure is higher than the straight structure owing to the active contact area between the warp and weft yarns increasing in the undulated structure. It can also be seen that the pull-out force of the steel wire is higher than that of carbon rovings, which is due to the higher stiffness of steel wire than that of carbon rovings. The results of th pull-out test show that MWSF possess sufficient stability, so that these structures can force-fittingly be infiltrated in a subsequent infiltration process.

## Conclusion

The objective of this research was to create a fundamental technological basis for the production of multi-material woven spacer fabrics. It succeeded in developing multi-material woven spacer fabric structures and producing selected structures based on steel wire as well as carbon roving on a modified needle ribbon weaving machine. Two types of profiled wire – trapezium and zigzag were used for the realization of multi-material woven spacer fabric from wire and carbon rovings in this research. The sliding resistance of the structures developed is evaluated by means of the pull-out test. The result of the pull-out test indicates that the pull out force of warp yarns from zigzag profiled wire is higher than that of the trapezium profiled wire due to the geometry of the profiled wire. Furthermore the pull-out force of the warp yarns from the undulated structure is higher than that of the straight structure. These multi-material woven spacer fabrics, due to their geometry and material properties, can be used in the automobile industry as hybrid sandwich constructions for impact and crash applications. Such fabrics can also be suitable as lightening protection and in high temperature resistance applications, for example in the aerospace industry. The result of this research work has formed the basis of the promising realization of multi-material woven spacer fabrics and their characterization in [13].

## Acknowledgements

*This article presents a sample of results from the research program B2 CoMeT (100117440) at Technische Universität Dresden, Germany. The authors would like to thank the European Center for Emerging Materials and Processes (ECEMP) for the financial support of the above-mentioned project.*

## References

1. Chen S, Long HR, Liu YH, et al. Mechanical properties of 3D-Structure composites based on warp knitted spacer fabrics. *AUTEX Res J* 2015; 15: 127-137.
2. Włodarczyk B, Kowalski K. Technology and Properties of Distance Five-layered Double-Weft-Knitted Fabrics with Elastomeric Threads. *Fibres & Textiles in Eastern Europe* 2014; 22: 68-73.
3. Chen S and Long HR. Investigation on compression properties of polyurethane-based warp-knitted spacer fabric composites for cushioning applications Part I: experiment. *Industria Textila* 2014; 65: 200-205.
4. Flemming M, Ziegmann G and Roth S. *Faserverbundbauweisen: Faser und Matrices.* Berlin, Heidelberg: Springer Verlag, 1995.
5. Vassiliadis S, Kallivretaki A, Psilla N, et al. Numerical Modelling of the Compressional Behaviour of Warp-knitted Spacer Fabrics. *Fibres & Textiles in Eastern Europe* 2009; 17: 56-61.
6. Soin N, Shah TH, Anand SC, et al. Novel “3-D spacer” all fibre piezoelectric tex-

tiles for energy harvesting applications. *Eng Environ Sci* 2014; 7: 1670-1679**.**
7. McCarthy BJ. *Textiles for Hygiene and Infection Control.* 1st ed. Cambridge: Woodhead Publishing, 2011, pp. 30-32.
8. Mountasir A, Hoffmann G and Cherif Ch. Development of weaving technology for manufacturing three-dimensional spacer fabrics with high-performance yarns for thermoplastic composite applications: An analysis of two-dimensional mechanical properties. *Text Res J* 2011; 81: 1354-1366.
9. Badawi SSAM. *Development of the weaving machine and 3D woven spacer fabric structures for lightweight composites materials.* PhD thesis, Technische Universität Dresden, Germany, 2007.
10. Torun AR, Mountasir A, Hoffmann G, et al. Production Principles and Technological Development of Novel Woven Spacer Preforms and Integrated Stiffener Structures. *Appl Compos Mater* 2013; 20: 275-285.
11. Mountasir A, Hoffmann G, Cherif Ch, et al. Mechanical characterization of hybrid yarn thermoplastic composites from multi-layer woven fabrics with function integration. *J Thermoplast Compos Mater* 2011; 25: 729-746.
12. Großmann K, Mühl A, Löser M. et al. New solutions for the manufacturing of spacer preforms for thermoplastic textile-reinforced lightweight structures. *Prod Eng Res Devel* 2010; 4: 589-597.
13. Sennewald C, Kaina S, Weck D, et al. Metal sandwiches and metal-matrix-composites based on 3D woven wire structures for hybrid lightweight construction. *Adv Eng Mater* 2014; 16: 1234-1242.
14. Kang KJ. Wire-woven cellular metals: The present and future. *Prog Mater Sci* 2015; 69: 213-307.
15. Kieselstein E, Weinrich T, Adam F, et al. Cellular metals based on 3D-wire structures. In: *6th International conference on porous metals and metallic foams*, Bratislava, Slovakia, 1-4 September 2009, p. 94.
16. Sennewald C, Hoffmann G, Cherif Ch. *Fabric structure with cellular construction.* Patent 0368835, US, 2015.
17. Hoffmann G, Anderson O, Böhm R, et al. Novel composites for hybrid lightweight constructions. In: *International ECEMP-colloquium*, Dresden, Germany, 25-26 October 2012.
18. Cherif C. *Textile Materials for Lightweight Constructions: Technologies-Methods-Materials-Properties*. Berlin, Heidelberg: Springer-Verlag GmbH, 2016, pp. 170-174.
19. Harald Uhlig Stahldraht GmbH, Specification sheet (18.01.2015).
20. Toho Tenax, http://www.tohotenax.com/tenax/en/products/standard.php (accessed 19.12.2015).

☐ ***Received 19.07.2016 Reviewed 08.08.2016***