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Fiber-Based 3D Cellular Reinforcing Structures for Mineral-Bonded Composites with Enhanced Structural Impact Tolerance

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***Abstract*—**The development of solutions to improve the resistance of buildings to short-term dynamic loads, particularly impact load, is driven by the urgent demand worldwide on securing human life and critical infrastructures. The research training group GRK 2250/1 aims to develop mineral-bonded composites that allow the fabrication of thin-layered strengthening layers providing available concrete members with enhanced impact resistance. This paper presents the development of 3D woven wire cellular structures that can be used as innovative reinforcement for targeted composites. 3D woven wire cellular structures are truss-like architectures that can be fabricated in an automatized process with a great customization possibility. The specific architecture allows this kind of structures to have good load bearing capability and forming behavior, which is of great potential to give strength against impact loading. An appropriate combination of topology and material enables an optimal use of thin-layered reinforcement in concrete constructions.

***Keywords*—**3D woven cellular structures, ductile behavior, energy absorption, fiber-based reinforced concrete, impact resistant.

I. Introduction

THE majority of buildings and infrastructures that are available or being designed are composed of concrete or steel reinforced concrete. Beside a number of advantages, one major drawback of this type of construction is its relatively limited resistance to short-term dynamic loads such as collision, explosion or earthquake. This is primarily caused by the brittleness of concrete material. Considering the steadily increased danger brought about by the occurrence of such dynamic loadings, for example because of natural catastrophes or terrorist attacks, there is an urgent demand worldwide on enhancing building safety to secure human life and critical infrastructures.

A great number of studies have been carried out, proposing different protection methods for concrete constructions against short-term dynamic loads. One approach is to increase the thickness of main structure to prevent this from being penetrated through by the load source [1]. Another approach is to introduce external absorbent systems that can effectively diminish damage on the main structure [2]], [[3]. Because of the massive construction and complex designing requirements, a common adoption of such systems in building industry is challenging. In order to meet the present safety demands, development of innovative protective solutions that are cost-, material- and space-effective as well as easy-to-install is essential. In this respect, the research training group GRK 2250/1 has the vision to develop mineral-bonded composites that can be applied as thin, flat strengthening layers on available concrete members to enhance their resistance to short-term dynamic loads, particularly impact load [4]. Among other elements, reinforcing structures have essential contribution in attaining desired composite properties. Therefore, a main research focus is the development of appropriate reinforcing structures that can provide the composites with sufficient energy absorption capability and ductility so that they are more resistant to dynamic loads. Beside significant mechanical properties, an economical, flexible, repeatable and automatized manufacturing technology of such reinforcements is required regarding industrial adoption of targeted composites.

Steel structures have been long employed as reinforcement for concrete construction. Generally, steel provides tensile strength, helping concrete to overcome the disadvantage of being brittle. To attain sufficient reinforcement in complex loading cases, steel members are usually formed into 3D truss structures using bending, welding as well as tying tools. Because of multi-stage and elaborated process, only simple structures can be obtained and conventional steel constructing method is not suitable for the fabrication of reinforcement for thin, flat strengthening layers. Recently, the introduction of textile reinforcements has gained increasing attention. The major advantage of employing textile technology is its flexibility in fabricating customized complex structures in an automated process. In addition, high-performance fibrous materials such as carbon and glass fiber can be employed, allowing the implementation of thin layered concrete structures in varied shapes [5]. At the moment, textile grids comprising of in-plane reinforcing elements (2D) are available. Experiments have shown that 2D textile reinforced concrete performs well when subjected to in-plane loads such as tension or bending [7]. To strengthen concrete members under impact, textile structures with out-of-plane or three-dimensional (3D) reinforcing elements are crucially needed.

A potential textile structure that can meet mentioned requirements is 3D woven wire cellular structure, developed recently by researchers at ITM [8]. Thanks to the flexible weaving technique, a variety of 3D wire cellular structures with customized reinforcing elements can be fabricated in an automatized process. In general, these structures have good

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forming behavior in different directions. Wire cellular structures are truss-like architecture; hence good load bearing capability can be expected. When being used in sandwich panel, they show high resistance to compression and impact loads [9]. For the application in thin-layered mineral-bonded strengthening layers under impact, it is essential to investigate appropriate designs and to establish an understanding on structure-material-relations of reinforcing structure. The development of 3D woven wire cellular structures that are suitable to reinforce concrete constructions is presented in this paper.

II. Topology Development of 3D Woven Wire Cellular Reinforcing Structures

A. Background

A substantial fundament for the development of efficient reinforcing structures is the failure analysis of concrete constructions under impact. When being struck by a hard impacting missile, a complex of loads is generated in the target concrete wall, including tension, compression, shear as well as bending. “Hard” impact results in both local damage and global dynamic response. Local damage consists of spalling of concrete from the front side and scabbing from the rear side together with missile penetration into the target. Perforation occurs if damage is sufficient. Global dynamic response of the target wall consists of flexural deformation, caused by residual kinetic energy of the impacting missile after missile deformability and target penetration. As the impact velocity increases, damage grade is intensified and local damage tends to be overwhelming [10]. Good impact resistant design practice consists of preventing excessive local damage and improving ductility of target structure to sufficiently withstand the absorbed energy.

3D woven wire cellular structures are composed of a number of planar meshes, in which straight metal wires are interlaced at a right angle to each other. These are in-plane elements. The binding of two adjacent meshes is attained by means of other sets of wires that interweave with both surfaces. In order to realize a fully open cell configuration, in-plane elements are arranged distant from each other, while binding wires are bent into 2D or 3D shapes and integrated in out-of-plane directions, setting the distance between adjacent meshes. Fig. 1 illustrates the formation principal of 3D woven wire cellular structures [11].

Notable characteristics of 3D woven wire cellular structures for the application as concrete reinforcement are:

- fully open structure, which is advantageous for concrete casting,
- good deformation capability,
- truss-like architecture, providing potentially good load bearing capability and
- anisotropic behavior, allowing the customization of load oriented reinforcing structures for particular loading case.

The topology development is aimed to systematically investigate possible configurations of 3D woven wire cellular structure regarding their feasibility as well as applicability in concrete constructions. As the topology has a significant influence on forming capability and mechanical properties of resulting structures, a qualitative analysis of potential contribution of various 3D woven wire cellular structure to impact resistant mineral-bonded composites will be given. This serves as a good basis for the formulation a design concept as well as for the determination, implementation and optimization of appropriate 3D cellular reinforcement that meet the requirements of impact resistant design practice.

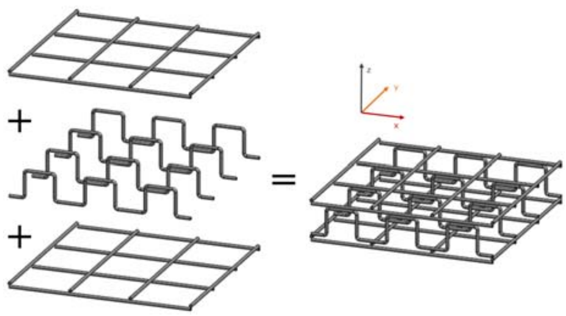

Fig. 1 Formation principal of 3D woven wire cellular structures

B. Single-Layered 3D Woven Wire Cellular Structures

As mentioned above, a complex of loads is generated in the target concrete wall during an impact event. To each single type of load, target concrete is strengthened using suitable load carrying elements that are arranged in appropriate position as well as direction of acting force. The inherent structural characteristics of 3D woven wire cellular structures allow the combination of various reinforcing elements in a complex structure.

In 3D woven wire cellular structures, in-plane elements are designated to provide the target concrete wall with tensile and bending strength. In a weaving process, in-plane elements are fed at a right angle to each other as warp and weft yarns, hence a biaxial reinforcement is attainable. As impact damage tends to occur in all directions, a symmetrical arrangement of strengthening elements is favorable. For this reason, equal distance is set between warp and weft yarns in all planar meshes. In contrast to in-plane elements, out-of-plane elements are expected to provide reinforcement against compression and shear. A further function of these elements is to bind adjacent planar meshes together to form a membrane structure that prevents structural delamination, enables layer-to-layer load dissipation and activates global structural dynamic response.

In this paper, 3D woven wire cellular structures are categorized based upon the number of out-of-plane systems constructed in the structure. The term “single-layered 3D woven wire cellular structures” refers to structures composed of two planar meshes that are connected by one in-between out-of-plane system. In one system, out-of-plane elements can vary in their shapes and arrangement. Because of the requirement on global uniform behavior, configuration of a single out-of-plane element remains unchanged. Selected possible single-layered 3D woven wire cellular reinforcing structures are depicted in Figs. 2 and 3.

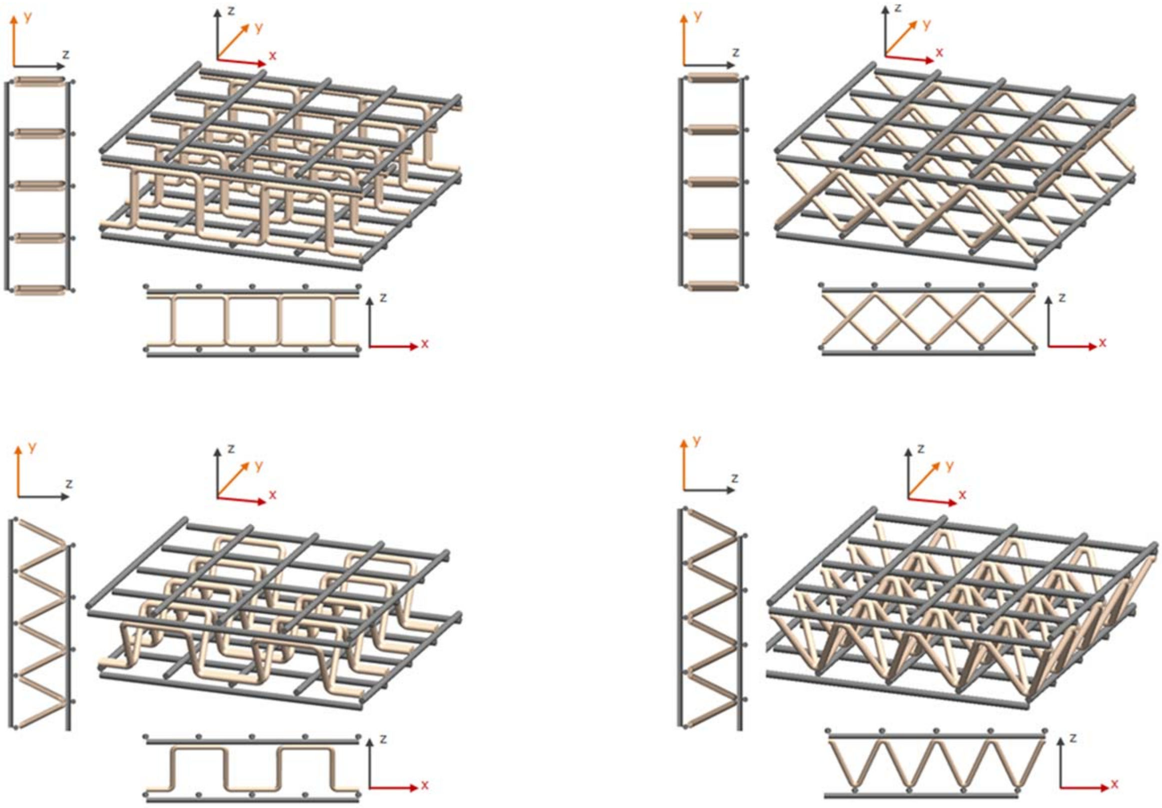

Fig. 2 Single-layered 3D woven wire cellular structures comprised of rectangular and triangular out-of-plane elements

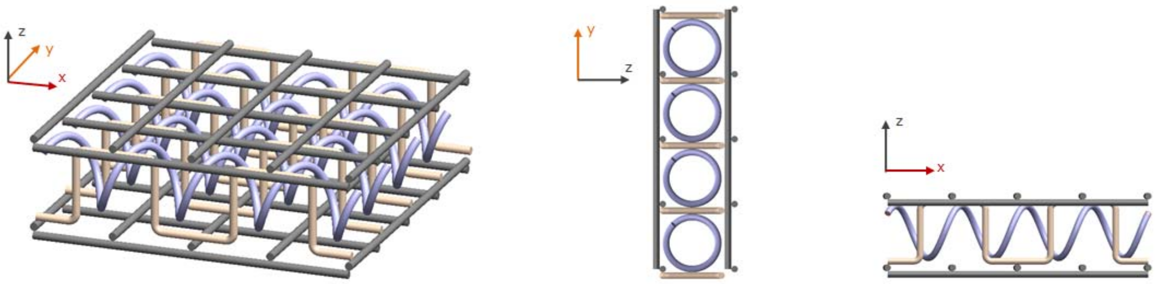

Fig. 3 Single-layered 3D woven wire cellular structure comprised of rectangular combined with helical out-of-plane elements

In Fig. 2, single-layered 3D woven wire cellular structures comprising of rectangular and triangular out-of-plane elements as well as their front and side views can be observed. Structures in the first row have out-of-plane elements that are arranged orthogonally to the top and bottom planes, forming truss-like structures that are commonly found in civil engineering. In the structures in the second row, out-of-plane elements are alternatively rotated through an angle ± 60° about the x-axis. Because of the diagonal disposal of out-of-plane elements, resulting structures potentially show better shear resistance and more effective load dissipating capability.

Beside 2D shapes, out-of-plane elements can also be made into 3D shapes. Employing helical springs makes resulting structure work as a damping system, which could be advantageous for enhancing flexural deformation or ductility of impact targeted concrete construction. It is possible to combine out-of-plane elements in 2D and 3D shapes, as can be seen in Fig. 3, so that good deformation and sufficient strength against compression can be attained. However, attention needs to be paid to ensure an even penetration of concrete matrix into the complex reinforcing structure.

C. Multi-layered 3D Woven Wire Cellular Structures

Multi-layered 3D woven wire cellular structures refer to structures having two or more out-of-plane systems arranged along the z-axis. The possible maximal layer number depends on the relation between requested thickness of target concrete wall and measurement of out-of-plane systems in the z-axis. In comparison to single-layered general 3D woven wire cellular structures, contribution of multi-layered reinforcing structures to the impact resistance of target concrete are expected to be considerably greater. An increase in the number of planar meshes in the structure leads to a multiplicate number of in-plane elements involving in the impact event, giving the target concrete more strength to withstand occurring loads. Meanwhile, structural deformability remains. The membrane effect would become more evident, whereby the impact energy descends gradually when reaching one reinforcing plane after another.

Fig. 4 illustrates exemplary double-layered 3D woven wire cellular structures. The upper cage structure is comprised of rectangular out-of-plane elements arranged orthogonally to the planar meshes. Diagonal triangular out-of-plane elements are employed to form the lower diamond structure. This structure is very well self-supported, can be formed without being collapsed. Because of the disposal of reinforcing elements in four different out-of-plane directions, diamond structures are expected to show high potential for heavy load bearing applications, especially when compression and shear are critical.

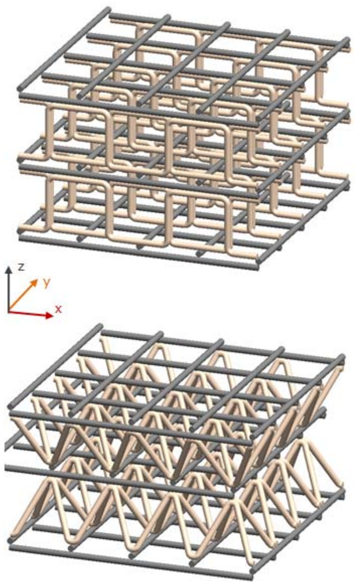

Fig. 4 Double-layered 3D woven wire cellular structures

III. Variations of 3D Woven Wire Cellular Reinforcing Structures

Using textile manufacturing technology, it is possible to introduce a wide range of variations on the basis of developed topology of 3D woven wire cellular structures. The aim is to further customize and enhance structural and mechanical properties so that reinforcing capability of resulting structures can be optimized for a particular use. Variable factors can be classified as following:

- Material type: In the fabrication of 3D woven wire cellular structures, fibrous metals are used as base material due to their capability of plastic deformation that is essential for the form stability of the structures. However, inherent strength of this material type is somewhat limited. This can be improved by means of hybrid structures in which high-performance materials such as glass or carbon filaments are integrated as in-plane reinforcing elements using textile process. Resulting structures possess all characteristics of 3D woven wire cellular structures with enhanced tensile and bending strength due to the availability of load oriented high-performance materials.
- Material parameters: In order to meet the property requirements of resulting structure, material parameters such as yarn count, yarn make-up can be adjusted.
- Structural parameters: Yarn density, cell size can also be adapted in weaving process to attain desired performance.

Fig. 5 depicts different variations of single-layered 3D woven wire cellular structure comprised of orthogonal rectangular out-of-plane elements towards the aim of enhancing the structure in-plane strength. In the upper structure, biaxial carbon meshes are integrated in the top and bottom surfaces to form a hybrid structure. In the lower structure, planar meshes are composed of double wires to increase the reinforcement ratio.

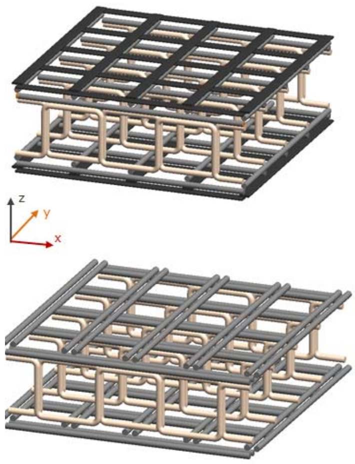

Fig. 5 Variations of 3D woven wire cellular structures

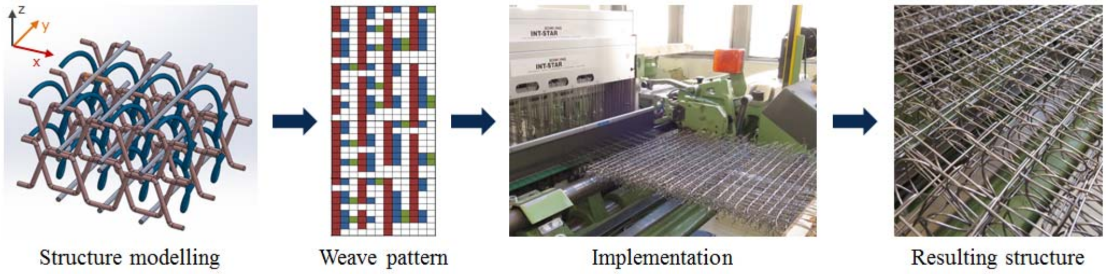

Fig. 6 Process chain to fabricate double-layered 3D woven wire cellular structures comprised of orthogonal trapezoids and helical springs

IV. Summary and Outlook

In this paper, the topology development and variations of 3D woven wire cellular structures are presented. Basis for the topology development is the failure analysis of concrete constructions under impact loading. In 3D woven wire cellular structures, in-plane and out-of-plane elements are employed at appropriate position and orientation to strengthen target concrete against different occurring loads such as tension, compression, bending and shear. The complex architecture is not only good load bearing but also deformable, allowing a global structural response. These characteristics have a great potential to contribute to the enhanced impact energy absorption capability of concrete constructions. Impact behaviors of 3D woven wire cellular structures are strongly influenced by structure topology, material and parameter selection. Multi-layered structures seem to be more promising due to a great number of reinforcing elements and possible layer-to-layer effects. Using textile manufacturing technology, it is possible to introduce a wide range of variations to 3D woven wire cellular structures such as creating hybrid structures and customizing reinforcing ratio to meet particular requirements. The topology development provides a substantial basis for impact resistant design practice. In the next step, selected 3D woven wire cellular structures will be fabricated and characterized, allowing a quantitative evaluation and determination of effective 3D woven wire cellular reinforcing structures for concrete construction with enhanced impact safety. The exemplary process chain to fabricate double-layered 3D woven wire cellular structures comprised of orthogonal trapezoids and helical springs is presented in Fig. 6.

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References

[1] R. P. Kennedy, "A review of procedures for the analysis and design of concrete structures to resist missile impact effects", *Nuclear Engineering and Design*, vol. 37, pp. 183–203, 1976.

[2] P. Hála, "Energy absorbing system made of high performance concrete", *Construction and Building Materials*, vol. 139, pp. 64–80, 2017.

[3] R. K. Faller et al., "High-impact, energy-absorbing vehicle barrier system", *United States Patent US 6,926,461 B1*, 2005.

[4] https://tu-dresden.de/bu/bauingenieurwesen/ifb/forschung/graduierten kolleg-2250-1, 25 Apr. 2018.

[5] https://www.bauen-neu-denken.de, 25 Apr. 2018.

[6] S. Scheerer, R. Chudoba, M. P. Garibaldi and M. Curbach, "Shells made of textile reinforced concrete – Applications in Germany", *Journal of the international association for shell and spatial structures*, vol. 58(1), pp. 79–93, 2017.

[7] J. Hegger, N. Will, O. Bruckermann, S. Voss "Load-bearing behavior and simulation of textile reinforced concrete", *Materials and Structures*, vol. 39(8), pp. 765–776, 2006.

[8] C. Sennewald et al., "Gewebestruktur mit zellularem Aufbau", *German Patent DE 10 2013 101 219 B3*, 2014.

[9] C. Sennewald et al., "Metal sandwiches and metal-matrix-composites based on 3D woven wire structures for hybrid lightweight construction", *Advanced Engineering Materials*, vol. 16(10), pp. 1234–1242, 2014.

[10] M. Y. H. Bangash, *Shock, Impact and Explosion – Structural Analysis and Design*. New York: Springer, 2008.

[11] C. Sennewald, *Generative Struktur-, Technologie- und Webmaschinenentwicklung für unikale zellulare 3D Strukturen in Leichtbauweise*. Dresden: TUDpress, 2016.