# A LATTICE MODELLING FOR TENSILE BEHAVIOUR OF TEXTILE-REINFORCED CONCRETE COMPOSITE
# MÔ HÌNH LƯỚI MÔ PHỎNG ỨNG XỬ KÉO CỦA BÊ TÔNG CỐT LƯỚI DỆT

Tran Manh Tien[1], Hoang Đinh Phuc[2], Pham Duc Tho[2], Cao Minh Quyen[3], Ngô Văn Thức[4]
*[1,2]Hanoi University of Mining and Geology, Hanoi, Viet Nam*
*[3]University of Transport Technology*
*[4]Mien Tay Construction University*
*DOI: https://doi.org/10.59382/pro.intl.con-ibst.2023.ses1-12*

TÓM TẮT: Vật liệu Composite nền xi măng đã được nghiên cứu một cách sâu rộng trong vài thập kỷ lại đây, được sử dụng như một kết cấu mới trong kỹ thuật xây dựng. Bài báo này giới thiệu kết quả mô phỏng số của mô hình lưới phần tử cho ứng xử kéo của vật liệu bê tông cốt dưới dệt, mà trong đó, mô hình ứng xử phá hủy vật liệu do nứt hoặc nghiền nát được sử dụng cho bê tông hạt mịn. Mô hình lưới được phát triển dựa trên dữ liệu thực nghiệm của các vật liệu thành phần trong các nghiên cứu có sẵn trên thế giới và được đối chứng với kết quả thực nghiệm của bê tông cốt lưới dệt tương ứng. Sự tương đồng kết quả mô phỏng số giữa mô hình lưới và các mô hình khác được làm rõ và phân tích. Từ mô hình lưới, ảnh hưởng của một vài tham số đến ứng xử kéo của bê tông cốt lưới dệt được xác định. Từ đó, một vài khuyến nghị được rút ra nhằm nâng cao các đặc tính cơ học của bê tông cốt lưới dệt.

TỪ KHÓA: Bê tông cốt lưới dệt, Mô hình lưới, Lan truyền vết nứt, Ứng xử kéo.

*ABSTRACTS: Textile-based composites have been studied extensively in the past two decades as they are used in constructing newly fabricated structural elements. This paper presents numerical results of lattice modelling of textile-reinforced concrete in which the damage behaviour model was considered by cracking or crushing for the cementitious matrix. The lattice model was developed from the input data of constitutive materials in the literature and validated with the corresponding textile-reinforced concrete composites. The agreement of numerical results between the lattice model and other numerical modelling was also highlighted and analyzed. From the lattice model, the effects of several parameters on the textile-reinforced concrete properties were identified by the parametric studies. From these results, several suggestions were concluded for enhancing the mechanical properties of the textile-reinforced concrete.*

*KEYWORDS: Textile-reinforced concrete; Lattice model; Crack propagation; Tension stiffening behaviour.*

## 1. INTRODUCTION

In the past two decades, textile-reinforced concrete (TRC) composite was increasingly and widely used in infrastructure construction. It is an alternative solution in materials engineering, which has breakthroughs and brings many economic and technical benefits. In addition, this material also ensures many criteria for sustainable development and is more environmentally friendly than fibre-reinforced polymer (FRP) composite. Textile-reinforced concrete is a combination of a substrate of fine-grained concrete (cementitious matrix) and reinforced by artificial textile meshes (reinforcement textile) in different natures such as carbon fibre, glass fibre, basalt, etc. The cementitious matrix works as a protective layer against the impact of the environment as well as transfers and distributes the internal forces in the reinforcement textile. The reinforcement textile with high mechanical performance ensures the stiffness and strength of TRC. So, this material offers advantages over reinforced concrete in terms of high tensile strength, less corrosion, lightness, etc. Therefore, it can also be applied to repair or strengthen existing structures as well as new load-bearing structures in bridges, buildings, traffic tunnels, etc. So, TRC composite is considered the material of the future in the industry. Infrastructure construction [1].

In the world, there are several studies on textile-reinforced concrete materials at both material and structural scales [2][3]. It has been used to reinforce/strengthen various types of reinforced-concrete structures and withstands various load cases such as earthquake, high temperatures, repetitive loads, etc. The results showed that the reinforcement efficiency of TRC composite is lower than that of FRP under normal conditions, but in special conditions such as high temperature, TRC has much more effective [4],[5],[6].

In Vietnam, TRC composite has been researched and applied in civil engineering in the last decade. At the material scale, several experimental studies have been carried out to determine the TRC's mechanical properties under direct tensile test or bending test at 3 points [7],[8],[9]. Cao Minh Quyen [7] compared two types of fine-grained concrete mixes in terms of strength and adhesion to glass textiles. The results showed that the aggregate composition, using Quartz powder and sand with the addition of fly ash to replace cement, gives the strength and stiffness approximately 1.3. times higher than that of the aggregate using composition with natural river sand. Le Minh Cuong et al. [8] fabricated and identified the mechanical properties of high performance fine-grained concrete reinforced by textile mesh for applying in bridge construction. The experimental results showed that the high tensile strength of textile-reinforced concrete can be used to reinforce the bridge structure.

At the structural scale, there were several studies aiming to identify the reinforcement efficiency of TRC composite when reinforcing the structure under bending, shear, compression, and puncture [10],[11],[12],[13],[14]. Nguyen Huy Cuong et al. [11] simulated the flexural failure of reinforced concrete beams reinforced with TRC. The simulation results, which have been compared with the previous experimental results, showed a significant reinforcement efficiency up to 180% related to the referent beam. Bui Thi Loan [13] has experimentally studied the behaviour of masonry sandwich structures reinforced with TRC under the effect of loads in the plane. The results showed that the reinforcement layers increased the stiffness of the masonry structure in the second phase. In addition, it increased the load-carrying capacity of the masonry to 36% as well as the deformation capacity of the structure up to 25%, compared to the unreinforced masonery.

The mechanical properties of TRC composite are generally identified from axial tensile or flexural tests. Most of the experimental results showed stress-strain curves with different working zones depending on several factors belonging from the mechanical characteristics of the constitutive materials as well as the together working between these materials. In addition, human factors also greatly influence the experimental results obtained. Therefore, to achieve the convergence of experimental results as well as to study the influence of material parameters on the mechanical behaviour of TRC composite, it needed a lot of experiments leading to high cost and time. Therefore, the research method by using numerical simulation is suitable to consider the influence of parameters (material, size, environment, etc.), both to reduce research time and costs and to ensure a guarantee of high reliability.

In the literature, several numerical models were developed and validated to consider the effect of many factors belonging to constitutive materials on the mechanical behaviour of TRC composite. Djamai et al. [15] have considered the failure mechanisms of the constitutive materials (cracking of cementitious matrix and debonding between textile/matrix) in multi-scale numerical modelling for the TRC sandwich panel (pull-out response of textile yarn in the cementitious matrix block and four points bending behaviour of TRC sandwich panel). Tran et al. [16] [17] [18] have used a cracking model for the cementitious matrix in the 3-D numerical modeling of the tensile behaviour of carbon TRC composite. Thanks this model, the effect of several parameters, such as the thickness of the cementitious matrix layer, the position and length of the deformation measured zone and elevated temperatures on the TRC's behaviour, has been highlighted and analyzed [17]. Almost these numerical studies were based on the finite element method (FEM) and the numerical results showed a good agreement with that in the experiment. They significantly contributed to our knowledge of numerical modelling on the mechanical behaviour of TRC and TRC-strengthened-structures.

However, simulation using FEM with a softening damage mechanical model may lead to mesh-sensitive results. An alternative approach for FEM with zero-thickness joint elements placed on all the edges of finite elements needs a very fine mesh to model correctly the crack pattern [19]. This limitation of the FEM can be overcome by using a lattice model, which has been shown to be mesh-independent [20]. Particularly, the lattice model is shown to be powerful for modeling the complex fracture process of concrete at both macroscopic and mesoscopic levels.

This paper presents numerical results of lattice modelling for textile-reinforced concrete in which the damage behaviour model was considered by cracking or crushing for the cementitious matrix. The lattice model was developed from the input data of constitutive materials in the literature and validated with the corresponding textile-reinforced concrete composites. From the lattice model, the effects of fracture energy on the TRC's behaviour were identified by a parametric study. The numerical result will also be compared with that of the FEM modeling.

## 2. LATTICE MODEL

### 2.1. Experimental data

The experimental results in ref [1] were used as input data for the development and validation of the lattice model. These were the tensile behaviour and mechanical properties of the constitutive materials and carbon TRC composites (F.GC1) at room temperature. Concerning this experiment, figure 1 shows the characterization method of the experimental works for the tensile behaviour of carbon TRC. The mechanical properties of constitutive materials (carbon textile and cementitious matrix) were also identified from this method. The input data is presented in table

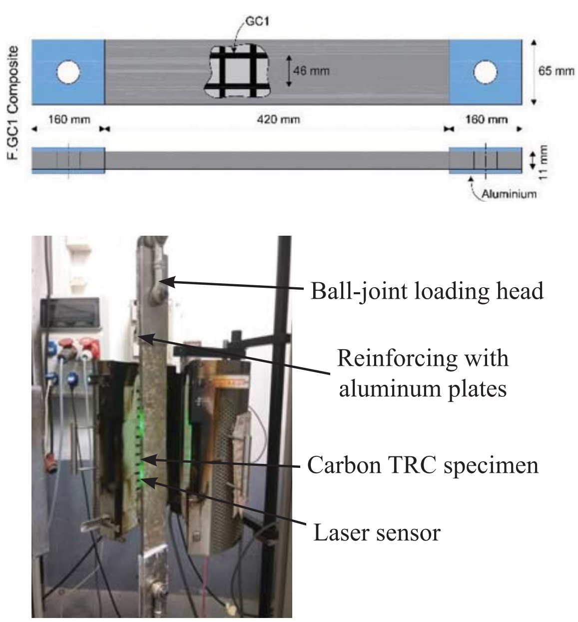


**Figure 1. Experimental works and F.GC1 specimen for the input data of lattice model [1]**

### 2.2. Modelling by lattice model

#### *2.2.1. Lattice model*

The spatial arrangement of the lattice elements and their cross-sectional properties in the lattice model is based on Delaunay and Voronoi tessellations [21], [22] of the domain shown in Figure 2.

Each node of mechanical element has three degrees of freedom that are two translations u and v and a rotation ϕ. The displacement jump at the centroid C of the element's mid cross-section relates to the nodal unknowns as follows:

$$u_c = B u_e \tag{1}$$

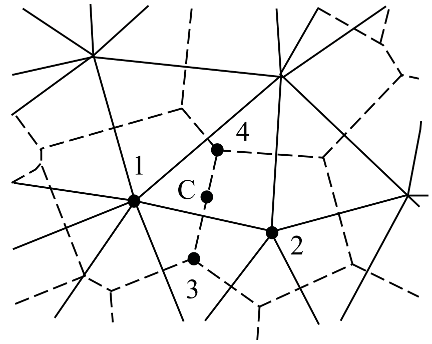


**Figure 2. Lattice model for fracture analysis**

Where

$$u_e = \{u_1, v_1, \varphi_1, u_2, v_2, \varphi_2\}^T \; ; \; u_c = \{u_c, v_c\}^T \tag{2}$$

$$B = \begin{bmatrix} -1 & 0 & e_c & 1 & 0 & -e_c \\ 0 & -1 & -h_e/2 & 0 & 1 & -h_e/2 \end{bmatrix} \tag{3}$$

The cross-section is determined by A = $l_e t$ where $l_e$ is length of mid-section, $t$ is the out-plan thickness and $D_e = \begin{bmatrix} E & 0 \\ 0 & \gamma E \end{bmatrix}$ is the moment of inertia.

The displacement $u_c$ is replaced by deformation $\varepsilon = u_c/h_e$, with $h_e$ is the length of the mechanical element. The rigid matrix of lattice element in the local coordinate system is determined by:

$$K = \frac{A}{h_e} B^T D_e B \tag{4}$$

Where $D_e$ is the elastic stiffness.

The stress-strain relation in the damaged mechanic framework reads:

$$\sigma = (1-\omega) D \varepsilon = (1-\omega)\bar{\sigma} \tag{5}$$

where ω is the damage variable; $\bar{\sigma} = (\bar{\sigma}_n, \bar{\sigma}_s)^T$ the stress vector; $D_e = \begin{bmatrix} E & 0 \\ 0 & \gamma E \end{bmatrix}$. For the plane stress condition, $E = \frac{\bar{E}}{1-\upsilon}$; $\gamma = \frac{1-3\upsilon}{\upsilon+1}$ with $\bar{E}$ and ν are Young's modulus and Poisson ratio. The variable ω is a function of a history variable κ, which is determined by the loading function:

$$f(\varepsilon, \kappa) = \varepsilon_{eq}(\varepsilon) - \kappa \tag{6}$$

The equivalent strain $\varepsilon_{eq}$ is defined as

$$\varepsilon_{eq}(\varepsilon_s, \varepsilon_n) = \frac{1}{2}\varepsilon_0(1-c) + \sqrt{(\frac{1}{2}\varepsilon_0(1-c)+\varepsilon_n)^2 + \frac{c\lambda^2\varepsilon_s^2}{q^2}} \tag{7}$$

where $s = f_s/f_t$, $c = f_c/f_t$, $f_t = E\varepsilon_0$ is the tensile strength, $f_s$ is the shear strength, $f_c$ is the compressive strength and $\varepsilon_0$ is the model parameters.

The loading-unloading condition is ensured by

$$f \le 0, \quad \dot{\kappa} \ge 0, \quad \dot{\kappa} f = 0 \qquad (8)$$

The softening curve is controlled by the fracture energies of pure compression $G_{fc}$ and of pure tension $G_{ft}$ for compressive and tensile conditions as follows

$$\sigma_n = f_t \, e^{\left(-\frac{\bar{e}}{\omega_i}\right)} \qquad (9)$$

with $i = c$ (compression) or $t$ (tension);

$\omega_i = G_{fi}/f_i$; $\bar{e} = \|e\|$ is the equivalent crack opening; $e$ is the crack opening vector defined by

$$e = h_e \omega \varepsilon \qquad (10)$$

### *2.2.2. Tensile test modeling*

Firstly, a model was built by code OFFEM with a configuration and geometric similar to the F.GC1 specimen as in experimental work. Then, all concrete and reinforcement textile elements were declared the corresponding material model and mechanical properties. Table 1 presents the mechanical properties of carbon textile and cementitious matrix used in the lattice model. Finally, the boundary conditions and loads were applied for the lattice model as in the experimental works. The fixed supports with all movements blocked according to three coordinated axes were applied for the first end. Then, all nodes on the other end were applied the imposed displacement with the rate of the applied load as in the experiment, controlled by the load steps and sub-steps. Figure 3 shows the configuration of the boundary condition and applied loading for the numerical model.

### 2.3. Numerical results

Figure 4 presents the stress-strain relationship of carbon TRC composite obtained from the lattice model in comparison with experimental results. The lattice model result shows the strain-hardening curve of tensile behaviour for carbon TRC with the cracking phase as described in the literature. In Figure 4, the cracking phase is characterized by the drops in axial stress in the stress-strain relationship. It means that the cracking model for the cementitious matrix simulated reasonably the response of this material as in reality. From the stress-strain relationship, the mechanical properties of carbon TRC were identified as like in experimental work. They were the stress and strain values at three notification points (I, II, UTS points) which characterized for three phases of the strain-hardening curve [23]. In comparison with the experiment, it could be found an agreement between both experimental and numerical results.

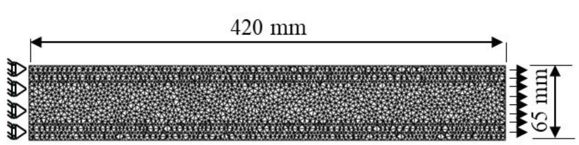


**Figure 3. Lattice model for carbon TRC's specimen**

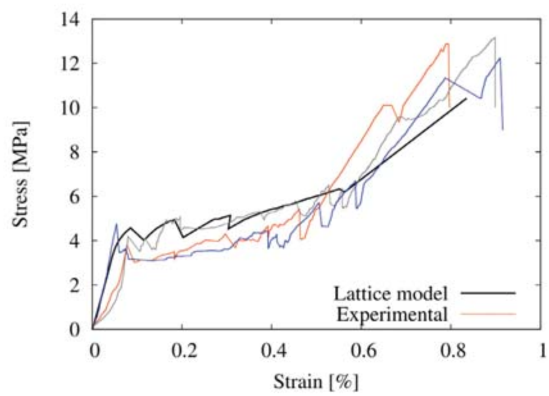


**Figure 4. Stress-strain relationship in comparison with experimental results**

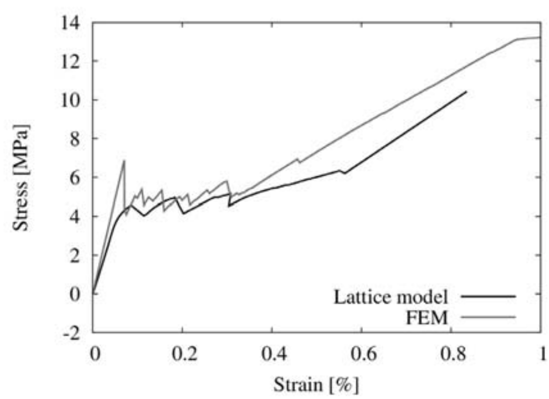


**Figure 5. Comparison between the lattice and FEM model results**

**Table 1. Input data for lattice model of Carbon TRC composite**

| Material | Mechanical parameters | | | | |
|---|---|---|---|---|---|
| | E [GPa] | $f_c$ [MPa] | $f_t$ [MPa] | $G_{ft}$ [J/m²] | $G_{fc}$ [J/m²] |
| Textile GC1 | 256 | | 2617 | | |
| Cementitious matrix | 30 | 32 | 3,5 | 5 × 102 | 6 × 106 |

## 3. DISCUSSION

### 3.1. Comparison with other numerical modeling

The numerical result obtained from the lattice model was compared with that of FEM model for carbon TRC composite [16]. The result showed a similar form of both strain-hardening curves with the cracking phase. However, it could be found in Figure 5, the ultimate strength from the lattice model was lower than that of FEM results. Other mechanical characteristics of carbon TRC composite were in good agreement between both numerical results.

### 3.2. Effect of fracture energy of cementitious matrix on TRC's behaviour

In order to consider the effect of fracture energy of the cementitious matrix on carbon TRC's behaviour, a parametric study was performed by increasing the value of this parameter from 0%, 10%, and 20% related to the initial value. Figure 6 presents the stress-strain relationship of carbon TRC composite obtained from the lattice model for three cases. From Figure 6, it could be found a similar form of strain-hardening curves of carbon TRC's behaviour. In the first phase (linear phase), no effect of fracture energy was found. However, with the higher value of fracture energy, the cracking phase of the stress-strain relationship was at a higher level. It means that the cementitious matrix contributed more to the mechanical capacity of the TRC specimen in this phase. In the last phase, the ultimate strength of the TRC specimen obtained from the parametric study ranged from 10 MPa to 12 MPa. This was doubted result of the lattice model because the cementitious matrix no contributes to the ultimate strength of the TRC composite after being completely cracked in the last phase, in general.

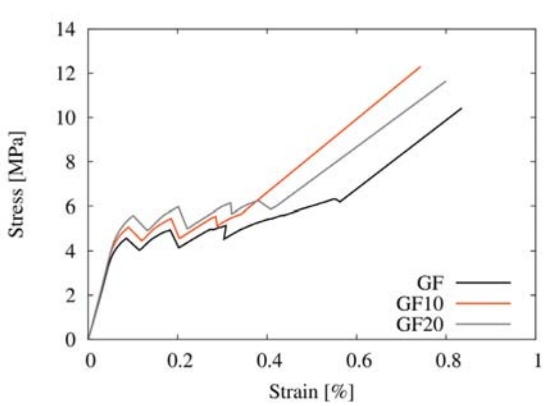


**Figure 6. Effect of fracture energy of the cementitious matrix on the TRC's tensile behaviour**

## 4. CONCLUSION

This paper presents the numerical results concerning the tensile behaviour of the carbon TRC composite by using a lattice model. Firstly, the lattice model was developed and validated with the previous experimental data in the literature. After that, the numerical result obtained from the lattice model was compared with FEM modeling. Finally, a parametric study was performed to identify the effect of the fracture energy value of the cementitious matrix on the TRC's behaviour. As numerical results, the following conclusions can be drawn from this work:

The lattice model could predict the strain-hardening behaviour of the TRC composite with the cracking phase characterized by the drop in stress. In comparison with experimental data, the lattice model result has a good agreement with the experiment and FEM model.

The effect of fracture energy value on the strain-hardening behaviour of the TRC composite increased progressively with the working phases. No effect was found in the linear phase, a higher level was in the cracking phase, and an obvious effect was in the last one.

## ACKNOWLEDGEMENTS

This work is financially supported by the Ministry of Education and Training of Vietnam, Grant No. B2022-MDA-08.

## REFERENCES

[1] M. T. Tran, *"Caractérisation expérimentale et modélisation numérique du comportement thermomécanique à haute température des matériaux composites renforcés par des fibres",* phdthesis, Université de Lyon, 2019. Accessed: Apr. 02, 2020. [Online]. Available: https://tel.archives-ouvertes.fr/tel-02341216

[2] Z. C. Tetta and D. A. Bournas, "TRM vs FRP jacketing in shear strengthening of concrete members subjected to high temperatures", *Compos. Part B Eng.*, vol. 106, pp. 190–205, Dec. 2016, doi: 10.1016/j.compositesb.2016.09.026.

[3] S. M. Raoof and D. A. Bournas, "TRM versus FRP in flexural strengthening of RC beams: Behaviour at high temperatures," *Constr. Build. Mater.*, vol. 154, pp. 424–437, Nov. 2017, doi: 10.1016/j.conbuildmat.2017.07.195.

[4] S. M. Raoof, L. N. Koutas, and D. A. Bournas, "Textile-reinforced mortar (TRM) versus fibre-reinforced polymers (FRP) in flexural strengthening of RC beams", *Constr. Build.*

*Mater.*, vol. 151, pp. 279–291, Oct. 2017, doi: 10.1016/j.conbuildmat.2017.05.023.

[5] T. Li, M. Deng, M. Jin, Z. Dong, and Y. Zhang, "Performance of axially loaded masonry columns confined using textile reinforced concrete (TRC) added with short fibers", *Constr. Build. Mater.*, vol. 279, p. 122413, Apr. 2021, doi: 10.1016/j.conbuildmat.2021.122413.

[6] Z. C. Tetta, L. N. Koutas, and D. A. Bournas, "Textile-reinforced mortar (TRM) versus fiber-reinforced polymers (FRP) in shear strengthening of concrete beams", *Compos. Part B Eng.*, vol. 77, pp. 338–348, Aug. 2015, doi: 10.1016/j.compositesb.2015.03.055.

[7] Cao Minh Quyền, *"Chuyên đề 1: Nghiên cứu thực nghiệm xác định một số tính chất cơ học của bê tông cốt lưới sợi"*. Jan. 2021.

[8] L. M. Cường and nnk, *"Nghiên cứu chế tạo và xác định các đặc tính cơ học và độ bền của bê tông hạt mịn tính năng cao cốt lưới dệt ứng dụng trong công trình cầu"*. 2018.

[9] N. H. Cường, N. Đ. Quang, and V. V. Hiệp, "Nghiên cứu thực nghiệm xác định ứng xử dính bám giữa lưới sợi các-bon với các loại bê tông hạt mịn sử dụng cát quartz và cát biển", *Tạp chí Khoa học Giao thông Vận tải*, vol. 59, 2017.

[10] H. X. Ba and P. D. Hữu, *"Phân tích thực nghiệm đánh giá ứng xử chịu cắt của dầm bê tông cốt thép được tăng cường bằng bê tông cốt lưới dệt sợi các bon",* 2017.

[11] Cường N. H., Hiệp V. V., and Dũng L. Đ., *"Nghiên cứu ứng xử chịu uốn của dầm bê tông cốt thép được tăng cường bằng bê tông cốt lưới dệt",* p. 7.

[12] N. X. Huy and N. T. Nhung, *"Phân tích sự phá hoại chọc thủng của bản bê tông cốt thép được gia cường bằng bê tông cốt lưới dệt",* 2019.

[13] B. T. Loan, *"Nghiên cứu thực nghiệm ứng xử của kết cấu sandwich tường gạch-bê tông cốt lưới dệt dưới tác dụng của tải trọng trong mặt phẳng",* 2018.

[14] N. Đ. Quang and nnk, *"Nghiên cứu ứng dụng bê tông cốt lưới dệt trong tăng cường kết cấu bê tông cốt thép ở vùng biển và hải đảo"*. 2018.

[15] Z. I. Djamai, M. Bahrar, F. Salvatore, A. Si Larbi, and M. El Mankibi, "Textile reinforced concrete multiscale mechanical modelling: Application to TRC sandwich panels", *Finite Elem. Anal. Des.*, vol. 135, pp. 22–35, Nov. 2017, doi: 10.1016/j.finel.2017.07.003.

[16] M. T. Tran, X. H. Vu, P. L. Dao, and D. T. Pham, "A 3-D finite element modeling for the textile-reinforced concrete plates under tensile load using a non-linear behaviour for cementitious matrix", *J. Sci. Technol. Civ. Eng. STCE - NUCE*, vol. 15, no. 1, Art. no. 1, Jan. 2021, doi: 10.31814/stce.nuce2021-15(1)-06.

[17] M. T. Tran, X. H. Vu, and E. Ferrier, "Numerical Modeling of Tensile Behaviour of Textile-Reinforced Concrete Composite Using a Cracking Model for Cementitious Matrix: Effect of Material Parameters", in *CIGOS 2021, Emerging Technologies and Applications for Green Infrastructure*, C. Ha-Minh, A. M. Tang, T. Q. Bui, X. H. Vu, and D. V. K. Huynh, Eds., in Lecture Notes in Civil Engineering. Singapore: Springer, 2022, pp. 783–792. doi: 10.1007/978-981-16-7160-9_79.

[18] M. T. Tran, X. H. Vu, and E. Ferrier, "Mesoscale numerical modeling and characterization of the effect of reinforcement textile on the elevated temperature and tensile behaviour of carbon textile-reinforced concrete composite", *Fire Saf. J.*, vol. 116, p. 103186, Sep. 2020, doi: 10.1016/j.firesaf.2020.103186.

[19] A. Pouya, "A finite element method for modeling coupled flow and deformation in porous fractured media", *Int. J. Numer. Anal. Methods Geomech.*, vol. 39, no. 16, pp. 1836–1852, 2015, doi: 10.1002/nag.2384.

[20] J. E. Bolander and N. Sukumar, "Irregular lattice model for quasistatic crack propagation", *Phys. Rev. B*, vol. 71, no. 9, p. 094106, Mar. 2005, doi: 10.1103/PhysRevB.71.094106.

[21] Peter Grassl, "A lattice approach to model flow in cracked concrete", *Cem. Concr. Compos.*, vol. 31, pp. 454–460, 2009.

[22] D. T. Pham, L. Sorelli, M. Fafard, and M.-N. Vu, "Hydromechanical couplings of reinforced tensioned members of steel fiber reinforced concrete by dual lattice model", *Int. J. Numer. Anal. Methods Geomech.*, vol. 45, no. 2, Art. no. 2, 2021, doi: 10.1002/nag.3148.

[23] M. T. Tran, X. H. Vu, and E. Ferrier, "Mesoscale experimental investigation of thermomechanical behaviour of the carbon textile reinforced refractory concrete under simultaneous mechanical loading and elevated temperature", *Constr. Build. Mater.*, vol. 217, pp. 156–171, Aug. 2019, doi: 10.1016/j.conbuildmat.2019.05.067.