Textile composite reinforcement forming analysis considering out-of-plane bending stiffness and tension dependent in-plane shear behavior

M. Nishi[a*, b], T. Hirashima[a], T. Kurashiki[b]

[a]*Engineering Division, JSOL Corporation, 2-5-24 Harumi, Chuo-ku, Tokyo, 104-0053, Japan*
[b]*Department of Management of Industry, Osaka University, 2-1 Yamada-Oka, Suita, Osaka 565-0871, Japan*
**nishi.masato@jsol.co.jp*

Keywords: Finite element analysis (FEA), Forming simulation, Textile reinforcement.

Abstract
In automotive industry, the use of carbon fiber reinforced plastic (CFRP) in mass production cars is gradually increasing because the developments of resin transfer molding (RTM) have reduced its cycle time to less than 10 minutes. Carbon textiles are usually used as a reinforcement in RTM. The carbon textile reinforcement is formed between forming dies as the first stage. In this study, we propose an FE model for textile reinforcement forming simulation that can express out-of-plane bending stiffness and tension dependent in-plane shear behavior in order to predict wrinkle accurately.

1. Introduction

The increasing requirement for crash safety with weight reduction in automotive industry expands the use of carbon fiber reinforced plastic (CFRP) gradually [1]. One of the reasons for the expansion is that the development of resin transfer molding (RTM) has reduced its cycle time to less than 10 minutes. RTM usually involves textile reinforcement and consists of three process stages. First, form the textile reinforcement. Second, inject resin into this preformed textile reinforcement and then, cure it to create the final composite part as the final stage. Finite element analysis (FEA) is essential to the vehicle design process, so numerical simulation of CFRP is strongly desired today. Especially forming simulation is important because the performance of the final composite part strongly depends on changes in fiber orientation during the forming process. Prediction of wrinkle as well as fiber orientation is important because wrinkles that occur during the forming process dramatically decrease the compressive strength.

The kinematic model [2] is most commonly applied in industry to predict the fiber orientation. This model is created using geometrical mapping algorithms. There are two main purposes to perform a textile reinforcement forming simulation. One is to understand the characteristics of fiber orientation after forming which affects the final performance of composite parts. Another is to predict a forming feasibility. In the kinematic model, the material properties such as nonlinear shear response and loading applications by blank-holder cannot be considered. The kinematic model can predict only fiber orientation and cannot describe any possible defects after forming. This scheme is not suited to incorporate processing condition during forming accurately.

Therefore, many researchers have studied a more accurate approach, FEA. Textile reinforcement consists of periodic architecture of yarns. This periodic architecture is called the representative volume cell (RVC). Skordos et al. [3] proposed a discrete model that combines truss elements within a RVC to represent uncoupled tension and shear properties. Aimene et al. [4] and Willems et al. [5] developed an anisotropic hyperelastic material model which independently calculates tension in the direction of warp and weft and in-plane shear for simulating the strong anisotropic behavior of textile reinforcement. Although out-of-plane bending stiffness plays important roles in describing wrinkles, the simulation models in many of existing researches do not consider this effect [3, 4]. In addition to out-of-plane bending stiffness, describing an accurate shear behavior is equally important because the in-plane shear deformation is a key deformation mode in forming simulation of textile reinforcement [5]. The in-plane shear property in the most simulation models is assumed to be independent from the tension along the yarn [3, 4] but the difference between picture frame and bias-extension tests suggests this to be an incorrect assumption as described below.

This study proposes a model for FEA that can consider the out-of-plane bending stiffness as well as in-plane anisotropic property of textile reinforcement. Furthermore a micromechanical model that introduces the stress component due to the yarn rotational friction is adapted to the proposed model to express the shear behavior that depends on the tensions in the yarns. To complete the study, the hemispherical preforming simulation is conducted and the proposed model is verified by means of comparing with the results of meso-scale model in order to showcase the capability of the method for evaluating wrinkles. The results using this proposed model are in good agreement with the meso-scale model results in two different forming conditions.

2. Out-of-plane bending

2.1. Out-of-plane bending stiffness of multi-scale material

In our previous study, we performed simulations using the meso-scale model under tensile, shear, compressive and bending deformations in order to understand each behavior. The tensile stiffness in yarn direction is much higher than the shear, compression and bending as shown in Figure 1. Furthermore, bending stiffness differs depending on the direction of the yarn [6].

The mechanical behavior of textile reinforcement is complex due to the intricate interactions of the yarns and fibers. It cannot be called a continuous material so bending stiffness cannot be deduced from in-plane properties as a continuous material.

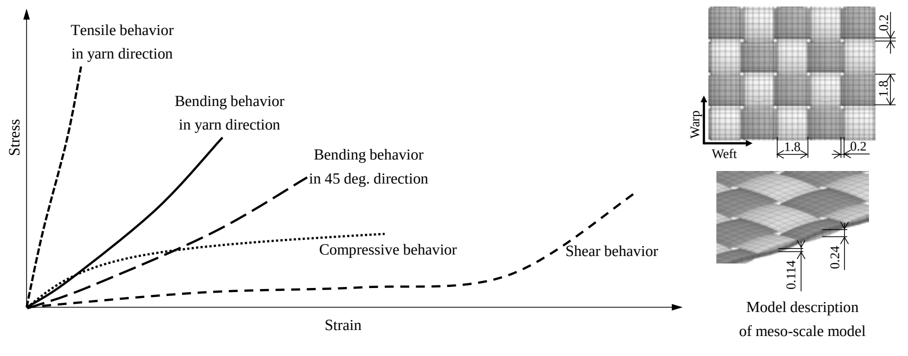

Figure 1. Mechanical behavior of textile reinforcement simulated by meso-scale model.

2.2. Modelling strategy to express out-of plane bending

Shell elements are usually used in metal forming simulation. The out-of-plane bending stiffness of a continuous material such as metal can be directly deduced from in-plane properties. However, the textile reinforcement simulation using shell elements shows that the derived bending stiffness is unrealistically high as compared with the experimental bending stiffness. Although the bending stiffness is often ignored as it is very low compared to tensile stiffness, more accurate simulation is achievable by considering bending stiffness in forming simulation. This improvement of the accuracy is especially remarkable for wrinkling as mentioned above.

Here we propose the shell and membrane combined model in order to consider the bending stiffness. Figure 2 shows the composition of our proposed model. In-plane properties are described by the membrane element and the bending stiffness is represented by a set of elements which consist of two shell elements with membrane element in between. Shell elements are duplicated on the membrane element to couple bending stiffness to it. The offset of the shell reference surface is applied to increases the effect of bending stiffness. As a result, we can give a small Young's modulus to the duplicated shell elements. It is enough not to affect the in-plane properties, but get effective bending stiffness. Figure 3 shows the calculation loop in this model. It is assumed that the bending stiffness is independently free from any in-plane deformations. The effects of off-axis bending stiffness can be calculated by giving an orthotropic material formulation to the duplicated shell element.

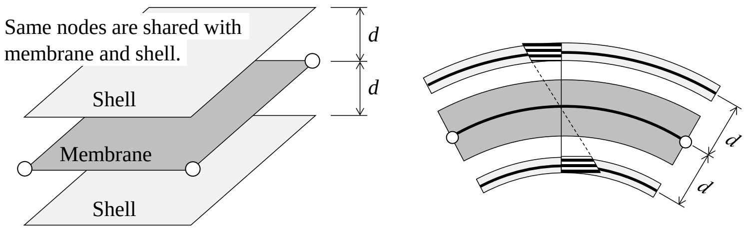

Figure 2. Macro-model considering in-plane and out-of-plane properties.

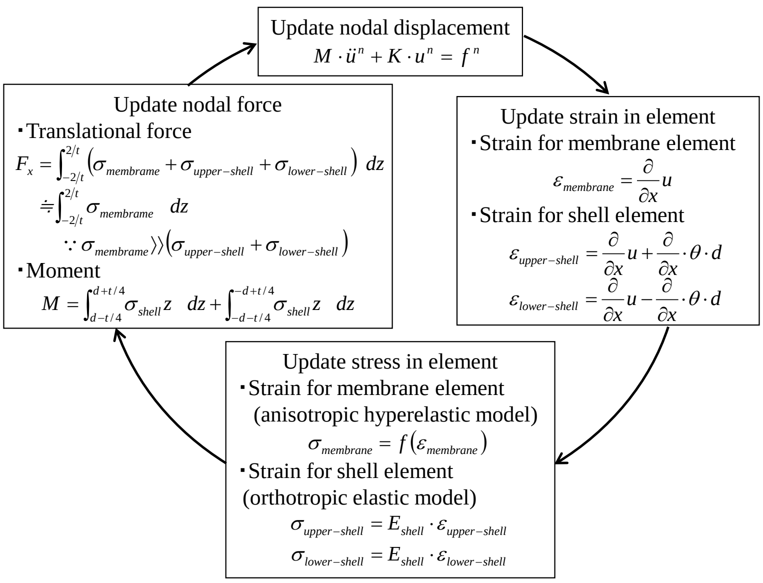

Figure 3. Calculation loop in proposed model.

3. In-plane shear

3.1. Tensile dependent in-plane shear behavior

A large in-plane shear deformation typically occurs during forming of textile since the in-plane shear resistance is very low until the shear locking angle. Thus accurately expressing the in-plane shear behavior of textile is very important for accurate forming simulation.

The required shear property data for textile forming simulation is usually extracted from either picture frame test or bias-extension test. However Launay et al. [7] reported the influence of the tension in yarn on the in-plane shear property by analyzing their proposed experimental equipment. So, in order to confirm the textile reinforcement bahavior under shear deformation, meso-scale simulations of the picture frame test and the bias-extension test are analyzed. Figure 4 (left) shows the differences of the responses between picture frame test and bias-extension. The significant difference of shear response between tests can be explained by the tension of yarns during each test as shown in Figure 4 (right). Much higher tension in yarn is observed in the picture frame test than the one in bias-extension test. We can understand the difference can be explained by tension of yarns.

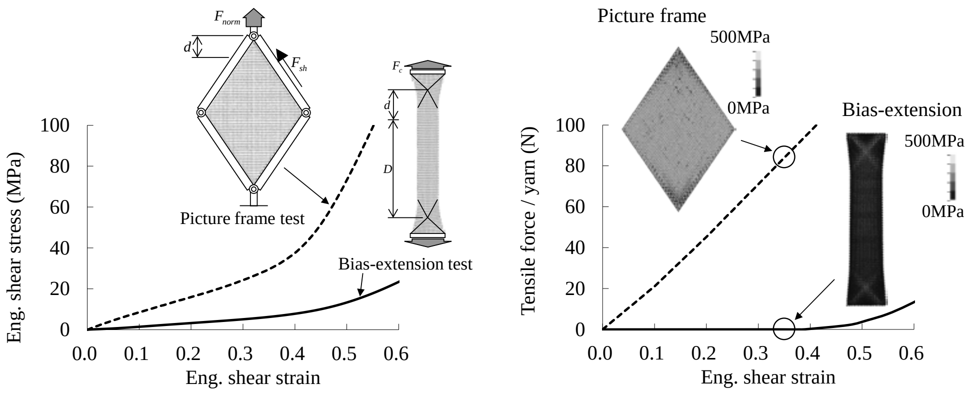

Figure 4. Shear responses (left) and fiber tensile load of yarn for picture frame test and bias-extension test (right).

3.2. Micromechanical Model for tensile dependent shear property

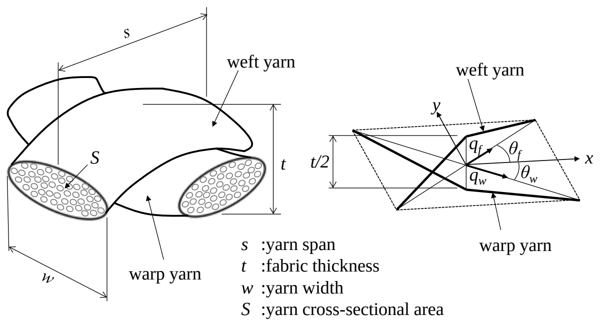

Figure 5. Representative volume cell of micromechanical model [7].

In this study, a micromechanical model proposed by Ivanov et al. [8] is adapted to the membrane element within our proposed shell and membrane combined model in order to describe the in-plane behavior. This model of woven textiles can account for the stress component due to the yarn rotational friction as well as the trellising with reorientation of the yarns and their locking. It means this model can also express the shear behavior that depends on the tensions in the yarns. The stress calculation of the micromechanical model that utilizes the RVC as shown in Figure 5 is explained below. The parameters of this model are the yarn span *s*, the textile thickness *t*, the yarn width *w*, the yarn cross-sectional area *S*, and the elastic constants of the yarn defined as a transversely isotropic elastic material.

1. The in-plane rotation of yarns is calculated by using the deformation gradient tensor.

2. The strain tensor of the RVC is transformed from RVC coordinate system to the yarn direction in order to determine the stress response of yarn.

3. The stress response of the yarns can be derived from the defined elastic constants of yarn. The transverse Young's modulus of the yarns and the longitudinal shear modulus are reduced to zero before the shear locking here.

4. The stress tensor based on the yarn material coordinate system is transformed into that on RVC coordinate system.

5. The stress components due to the friction are added to the stress components from the yarns.

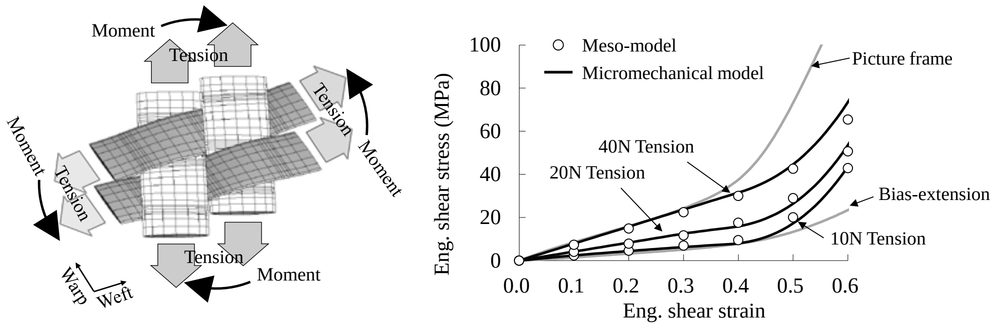

Figure 6. Meso-model to verify the tensile dependent shear behavior (left) and Shear responses under various tensile loads (right).

Using the meso-scale model in Figure 6 (left), shear deformation is disposed with tensile load equal to 10, 20 and 40 N per yarn. Interaction between yarns is simulated by contact calculation with Coulomb's friction model. The results of the meso-scale simulation show that the shear resistance is increased by the tension in the yarns and the shear response of micromechanical model also increases when increasing the tension in yarns. The tension dependent shear behavior of micromechanical model shows good agreement with those of meso-scale model as shown in Figure 6 (right).

4. Application to single layer forming simulation

4.1. Influence of out-of-plane bending stiffness on the wrinkle during forming

Blank-holder is usually used to reduce the wrinkles. But as a first step, the hemispherical forming simulations are conducted without a blank-holder in order to verify the influence of the out-of-plane bending stiffness upon the wrinkles under a severe condition, using both the meso-scale and the proposed model. The size of the blank sheet of textile reinforcement is 156 mm x 156 mm. The radius of the hemispherical part of the punch is 50 mm and the travelling distance of the movable punch is 30 mm.

Figure 7 shows the FE model and the deformed shapes of the meso-scale model. The model which consists of only membrane element is also calculated to investigate the effect of the bending stiffness. In this model, only in-plane property is considered. The proposed model considers an out-of-plane bending stiffness as well as in-plane property. The material properties defined in these models is derived from meso-scale simulation [6]. Many small wrinkles are observed in the model which considers only in-plane property. The shapes of wrinkles in the proposed model are similar to the one in the meso-scale model. Here the simulations demonstrate that the bending stiffness plays a very important role in the shapes of wrinkles.

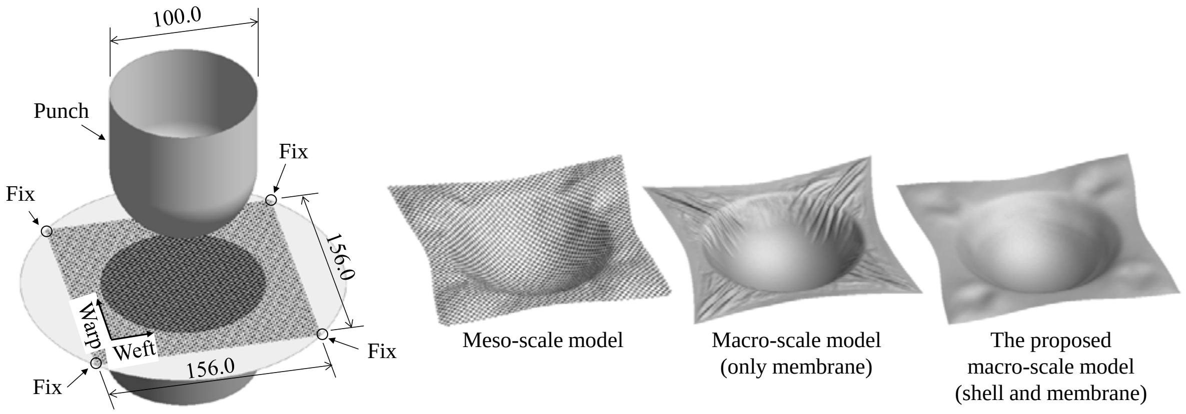

Figure 7. FE model without blank-holder and comparison of wrinkles between meso-scale model, model which considers only in-plane property, and the present proposed model.

4.2. Influence of shear behavior on the wrinkle during forming

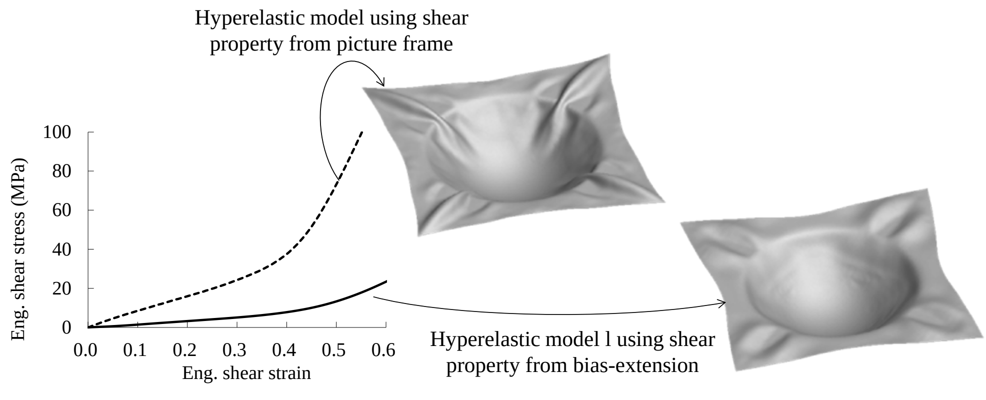

Figure 8. Comparison of results using shear properties between picture frame test and bias-extension test.

An anisotropic hyperelastic material model is applied to the membrane element in our previous work [6]. Whereas the shear property defined in this model is usually derived from either the picture frame test or bias-extension test, the shear property extracted from each test is significantly different due to the tension in yarn as the mentioned above. The simulation results using each shear property are shown in Figure 8. The shapes of the wrinkles are considerably different. The comparison between wrinkles shown in Figure 8 and in meso-scale model in Figure 7 ensures that the use of the shear property extracted from bias-extension test is suited to this condition. This is reasonable because the tensile load of yarns almost does not occur during forming. The proposed model applied the micromechanical model mentioned in the last section shows good agreement with meso-scale model as shown in Figure 7 (right)

Next, the forming simulations with a blank-holder are conducted in order to verify the wrinkles under the different forming condition where the tensile load of yarns occurs during forming. In this case, the size of the blank sheet of textile reinforcement is 180 mm x 180 mm and the travelling distance of the movable punch is 50 mm. Figure 9 shows the forming condition and the deformed shapes of the anisotropic hyperelastic material model using the shear properties from a picture frame test (upper left), a bias-extension test (upper right), the meso-scale model (lower left) and the proposed model applied the micromechanical model (lower right). The wrinkles in the hyperelastic material model which uses the shear property from a picture frame test is more similar to one of meso-scale model than the result using a bias-extension test because the shear response during this forming condition is more similar to the one from a picture frame test in which the higher tensile load of yarns occurs during the shear deformation. The proposed model shows good agreement with meso-scale model under the conditions with a blank-holder as well as without a blank-holder.

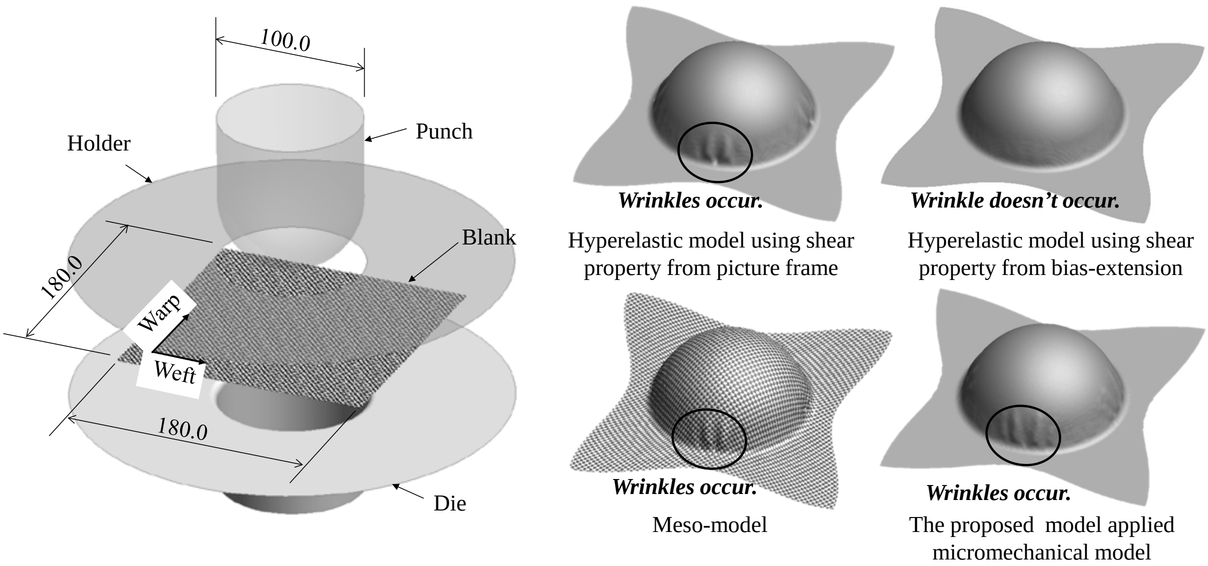

Figure 9. Comparison of results with a blank-holder.

5. Conclusion

An FE model for the forming of textile reinforcement was proposed in this study. The proposed model overcame the bending stiffness by placing shell elements on either side of membrane element. Furthermore, the micromechanical model applied to the membrane element enabled the membrane element to express the shear behavior which depends on the tensions in the yarns. It is because this micromechanical model introduces the stress component resulting from the yarn rotational friction. To verify the proposed model, the hemispherical forming simulations were conducted with two different boundary conditions for a purpose of comparison of the proposed model with the meso-scale model. The proposed model showed in good agreement with the meso-scale model. The results of sensitivity studies showed that an accurately described a bending stiffness and shear behavior were very important for evaluating the wrinkles.

RTM process is the most popular manufacturing process in automotive industry now. On the other hand, thermoforming of continuous fiber reinforced thermoplastic prepreg have increased its presence in the industry since it is a faster manufacturing process than RTM process which needs a long curing stage. The cycle time of the thermoforming process can be in the range of 1 minute. Thermoforming simulation for thermoplastic prepreg is complex because the material shows the temperature and rate dependent behavior as well as anisotropic and nonlinear behavior. The possibility of extending this proposed model which can express out-of-plane bending stiffness and tension dependent in-plane shear behavior to the thermoforming simulation is currently investigated.

References

[1] L. Ulich and P. Fairley, Carbon car [2013 Tech To Watch], *IEEE Spectrum*, 50(1), 30-31 (2013).

[2] M. Aono, D.E. Breen and M.J. Wozny, Fitting a woven-cloth model to a curved surface: mapping algorithms, *Computer-Aided Design*, 26(4), 278–292 (1999).

[3] A.A. Skordos, C.M. Aceves and M.P.F. Sutcliffe, A simplified rate dependent model of forming and wrinkling of pre-impregnated woven composites, *Composites Part A: Applied Science and Manufacturing*, 38(5), 1318-1330 (2007).

[4] Y. Aimene, B. Hagege, F. Sidoroff, E. Vidal-Salle, P. Boisse and S. Dridi, Hyperelastic approach for composite reinforcement forming simulations, *International Journal of Material Forming*, 1(1), 811-814 (2011).

[5] P. Boisse, B. Zouari and J.L. Daniel, Importance of in-plane shear rigidity in finite element analyses of woven fabric composite preforming, *Composites Part A: Applied Science and Manufacturing*, 37(12), 2201-2212 (2006).

[6] M. Nishi and T. Hirashima, Approach for dry textile composite forming simulation, *Proceedings of 19th International Conference on Composite materials (ICCM-19)*, 7486-7493 (2013).

[7] J. Launay, G. Hivet, A.V. Duong and P. Boisse, Experimental analysis of the influence of tensions on in plane shear behavior of woven composite reinforcements, *Composites Science and Technology*, 68(2), 506-515 (2008).

[8] I. Ivanov and A. Tabiei, Loosely woven fabric model with viscoelastic crimped fibres for ballistic impact simulations, *International Journal for Numerical Methods in Engineering*, 61(10), 1565-1583 (2004).

[9] J.O. Hallquist, LS-DYNA Theory Manual, LS-DYNA Theory Manual (2006).