1 Introduction
Non-crimp fabric (NCF) composite is one of remarkable materials because it has some advantages such as the improvement of out-of-plane strength due to effects of stitching yarns. The stitching technology offers the potential for substantial weight and cost reduction in complex and highly loaded composite structures. Several works have been reported in the literatures regarding FE-based model of NCF composites. Tserpes et al. reported a meso-mechanical approach of NCF composite structural parts based on RVE (representative volume elements) and homogenized progressive failure analysis [1]. Himmel et al. developed a FE based unit-cell model considering the thickness and fiber orientation of the layers and the shape and size of resin pockets [2]. Mikhaluk et al. reported a multi-scale FE homogenization to obtain effective mechanical properties of NCF composites with account of resin-rich zones and various fiber volume fraction values [3]. The previous research about mechanical characterization of woven fabric composites established theoretical and experimental investigations, which were based on mechanical behavior at macro scale which means "composite part scale" [4-6]. In order to evaluate fiber cracking, resin failure, delamination which relate to meso and micro scale structures, the recent studies have tried to generate more detailed FE models based on meso scale which means "fiber geometric scale" and micro scale which means "filament scale" [7]. However, Non Crimped Fabric (NCF) and woven composites have many design parameters such as volume fraction of fiber, architecture of reinforced fibers, matrix properties, etc. Furthermore, it is very difficult to evaluate the mechanical behaviors because of the complicated geometrical shape. Many applications require a notch for a joining of a NCF composite either to another NCF composite or to metal which is often fastened by bolts. It is very difficult to evaluate the mechanical characterization of notched NCF composites because of not only their heterogeneous characteristics, complex structures but also stress concentration around the hole. For an evaluation of mechanical property of textile composites with several parameters, FEM is one of effective methods in order to reduce the development times and the costs.

We have been developing a simulation procedure for mechanical behaviors for NCF based on Mesh superposition method which is one of the multi-scale analytical methods. The proposed method has applied to stitched laminate composites with/without a circular hole under static tensile loading. The numerical and experimental results are described in the paper.

2 FE Modeling for NCF Composites
2.1 Numerical Modeling
In order to estimate the mechanical behavior of NCF composites, the geometrical model and FE model had been generated as follows;
The geometrical data of NCF is generated by WiseTex software in Fig.1, which has been developed by Lomov et. al [8]. FE modeling of NCF is implemented by MeshTex in Fig.2, which is the FE modeling software for fiber reinforced composites developed by Zako, etc [9]. Since the geometry of NCF is complex, it is not easy to generate FE models integrally. Therefore, the
stitching yarn part and laminates part are modeled individually. In order to consider the interaction of each part, the mesh superposition method is applied to the FE analysis in Fig.3.

2.2 Mesh Superposition Method

In the mesh superposition method, the stitching yarn is defined as local mesh, and laminate model is treated as the global mesh. The analytical area is divided into global area ($\Omega^G = \Omega \setminus \Omega^L$) and local area ($\Omega^L$) as shown in Fig.4. $\Omega^G$ is the area where only global mesh is exists, and $\Omega^L$ is the area determined both global mesh and local mesh. The boundary between two meshes is defined as $\Gamma^{GL}$, and surface forces affect not $\Gamma^{GL}$ but only the external boundary ($\Gamma^S$), because $\Omega^L$ is perfectly inside $\Omega^G$. On those assumptions, the stiffness equation is represented as shown in Eq.(1).

This method has some advantages. The local-mesh can be superimposed on a macro-mesh without considering the matching of boundary for each mesh.

$$\begin{bmatrix} [K^G] & [K^{GL}] \\ [K^{LG}] & [K^L] \end{bmatrix}\begin{bmatrix} [d^G] \\ [d^L] \end{bmatrix} = \begin{bmatrix} [F^S] \\ [0] \end{bmatrix} \tag{1}$$

Each argument in Eq.(1) is indicated with the following equations.

$$[K^G] = \int_{\Omega^G} [B^G]^T[D^G][B^G]d\Omega$$

$$+ \int_{\Gamma^{GL}} [B^G]^T[D^G][B^L]d\Gamma$$

$$[K^{GL}] = \int_{\Gamma^{GL}} [B^G]^T[D^G][B^L]d\Gamma$$

$$[K^{LG}] = \int_{\Omega^L} [B^G]^T[D^G][B^L]d\Omega$$

$$[K^L] = \int_{\Omega^L} [B^L]^T[D^L][B^L]d\Omega$$

$$[F^S] = \int_{\Gamma^S} [N^S]^T\{f\}d\Gamma.$$

Where, $[N]$ and $\{d\}$ have been shape function matrix and displacement respectively, and suffix $G$ and $L$ have represented the domain of global and local. $[B]$
is strain-displacement matrix, and $[D]$ is stress-strain matrix.

3 Static Tensile Test

3.1 Stitching Pattern

The test specimen has been prepared as glass fiber / polyester composites. Figure 5 shows the stitching pattern and geometry of a specimen for NCF composites. The stitching pattern is a promat type, and the structure has the opening resin region due to the insertion of stitching yarns. It is clear that the shape is channel type by the observation of the specimens.

In order to estimate the stitching parameters on mechanical characteristics of NCF, the test specimens had been prepared with changing the several stitching parameters. The first parameter is a stitching pitch (2, 6 course) in Fig.6, the second is stacking sequence ([0/90)s], [(90/0)s]) in Fig.7, and the last is the tensile direction (MD: machinery direction, CD: cross direction).

3.2 Geometry of Opening Resin Region

The geometry of opening resin region is measured by microscope. Figures 8, 9 show the observational results of geometry of opening resin region. The width of channel is quite different due to the stitching pitch. In [0] ply, the width in 6 course is wider than that of 2 course due to the tension force of stitching yarn as shown in Fig.8(b). On the other hand, the width of channel in 6 course is narrow due to the stitching pitch in the case of [90] ply. The volume fraction of fiber observed by microscope in each ply is shown in Fig.10. The volume fraction is almost 59%, however, there are high volume fraction in case of [0] ply (6 course) of [(0/90)s]MD and [90] ply (6 course) of [(90/0)s]CD due to the effect of opening resin region.

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Fig.5 Geometry of NCF specimen with promat stitching

Fig.6 NCF composites with different stitching pitch

Fig.7 NCF composites with different stacking sequence
To estimate the effects of stitching parameters on mechanical characteristics of NCF with a circular hole, the tensile test and numerical simulation have been carried out. The material is quite same in Fig.5, and the geometry of the specimen is based on ASTM D 5766. The diameter of a hole is 6 (mm). Figure 11 shows the geometry of specimen.

### 3.3 Geometry of Test Specimen

Fig. 8 Geometry of opening resin region in [(0/90)s]MD

Fig. 9 Width of channel resin

Fig. 10 Volume fraction of fiber

Fig. 11 Geometry of test specimen
4 Experimental and Numerical Results

4.1 Experimental results

Figure 12 shows the experimental results of the stiffness reduction in case of [(0/90)s] MD specimens with a hole. As the comparison, the experimental results without a hole are shown in Fig.13. The effects of stitching parameters on mechanical behaviors are not so large compared with the results without a hole.

![Figures 12 and 13 showing experimental results with and without a hole](image)

Figure 14 shows the relation between number of transverse cracks and applied strain in case of [(0/90)s] MD 2 and 6 course with a hole. In the figure, ‘TC’ means the transverse crack, and ‘SP’ is splitting. The cracks had been counted with the images by In-situ observation. The relation of cumulative energy of acoustic emission (AE) and the strain is also shown in the figures. The tendency of the increase of transverse cracks and AE signals are almost same. In case of [(0/90)s] MD 6 course, the number of transverse cracks and splitting increase earlier than those of 2 course.

![Figure 14 showing relation between cracks, AE energy and strain](image)

4.2 Numerical results

Figure 15 shows the FE mesh of a NCF composite with a hole which is generated by WiseTEX and MeshTEX. The NCF composites are treated as heterogeneous bodies with anisotropy for fiber bundles and with isotropy for matrix, respectively. The isotropic damage model is applied for matrix, and anisotropic damage model is applied for the fiber bundle. The occurrence of damage can be predicted by Hoffman’s criterion.

![Figure 15 showing FE mesh of NCF composite](image)
Figure 16 shows the numerical results of stiffness reduction for [(0/90)s] MD with considering a hole. Furthermore, the stiffness reduction without considering a hole is shown in Fig. 17. As the comparison, the stiffness reduction of FEM and experiments are shown in Fig. 18. The tendency is almost same with the experimental and numerical results.

Figure 19 shows the numerical results of damage development and experimental results with In-situ observation. The colored parts in numerical results mean the damaged elements judged by the criterion of Hoffman. The initial transverse cracks appear around the opening resin region perpendicular to the loading direction. The effects of the position of opening resin region and a hole on the damage development can be estimated with the proposed mesh superposition method. The initiation of damage and evolution of splitting are influenced due the position of a hole.

Figure 20 shows the numerical examples of NCF with changing the position of a hole and stitching yarns. The stress distribution of [(0/90)s] MD model under $\varepsilon=0.05\%$ is shown in the figure. To make clear the stress distribution in the model, the stress $\sigma_x$ in [0] ply is only illustrated.
The stress distribution around a hole of type A (Red circle in Fig.20(a)) is reduced due to the geometry of the opening resin region and a hole. Therefore, the initial stiffness has the broad dispersion due to the position of a hole and opening resin region.

5 Proposal of Numerical Modeling for NCF with a Hole based on Mesh Superposition Method

5.1 Numerical modeling

In order to estimate the effect of position of a hole and opening resin region on damage development of NCF composites conveniently, a new modeling of NCF composites with a circular hole is proposed based on the mesh superposition method. The laminate parts and a hole part are modeled individually, and the mechanical behaviors under tensile loading is estimated. Figure 21(a) shows the continuous model of NCF GFRP with a hole as the conventional model, and the stitching pattern is tricot. On the other hand, the super imposed model which is consisted of global model (lamine with opening resin region) and local model (a hole part) is generated. The finite elements for the local model have low stiffness.

Figure 22 shows numerical results of stiffness reduction for the continuous model and super imposed model. There are same tendency with both results. The initial stiffness and the strain of initial failure are good agreement with super imposed model and continuous model.

The distribution of damage of [0] ply under $\varepsilon=0.3\%$ is shown in Fig.23. The black parts mean the damaged elements. The distribution of damage of super imposed model is almost same with the continuous model. As the results, the effects of the
position of opening resin region and a hole on the
damage development can be estimated with the
proposed mesh superposition method.

![Load direction](image1)
(a) Continuous model

![Load direction](image2)
(b) Super imposed model

Fig.23 Damage distribution of [0] ply under $\varepsilon=0.3\%$

6 Conclusions
The numerical models of stitching yarn and laminates with a circular hole are generated individually, and the mesh superposition method is applied to the FE analysis. From the numerical results, the mechanical behaviors of NCF composites with a hole can be estimated, and the stiffness reduction under static bending has same tendency with the numerical and experimental results. Furthermore, a new modeling of NCF composites with a circular hole is proposed based on mesh superposition method in order to estimate the effect of position of a hole and opening resin region on damage development conveniently. From the results, it has been revealed that the proposed numerical modeling method is useful for design of the products composed of textile composites.

Acknowledgement
The authors would like to express our thanks to Prof. I.Verpoest and Prof. S.V.Lomov (Katholic University Leuven, Belgium) for their cooperations.

References