1 Introduction
An increasing demand of Carbon Fiber Reinforced Polymer (CFRP) parts in industry involves improving technics and methods for more efficient part processing. The preforming processes of CFRP components made of Non-Crimp Fabrics (NCF) can be accelerated by draping into the mold multiple dry NCF plies in a single step. The difficulty in handling loose NCF ply stacks can be overcome by joining the plies together. Thus, the stability of the ply stack can be improved by using an assembly seam, also called “local stitching” (Fig. 1). However, the stitching influences the draping behavior of the ply stack, resulting in a more challenging prediction of the final preform shape [1].

The presented work shows a way to model and simulate the draping process of dry stitched NCF plies by the Finite Element Method (FEM). Employing the software PAM-Crash® (ESI Group®) on a macro-scale level, every NCF ply is modeled by a single shell layer. Material model MAT 140, a bi-phase shell material card, is used to model these NCF plies. Specific 1D-elements are used to represent the seam between the plies. Tests to characterize the properties of the assembly seam are carried out. Model development is made with the simulation of these two tests: bias extension test [2] and single lap shear test (Fig. 2). Validation is made by comparing the fiber orientations after forming of both simulated and experimental results with an automated reproducible measuring system named EuroPAS (Eurocopter Preform Analysis System) [3]. To do so, a generic double curved helicopter frame is formed by a double diaphragm forming process [4].

1.1 Preliminary studies
Simulations in preliminary studies showed that the structural stitching influenced the general draping behavior of the material (Fig. 3). Indeed, when compared to non-stitched ply stacks, it was noticed that the stitching prevented the relative sliding of the plies and thus limited the shearing behavior. As a consequence, the simulations showed that stitched ply stacks were less deformable and then, their drapability more difficult. Furthermore, it was shown that the occurrence of defects during forming was dependent of the stitching accuracy.

1.2 Simulation of local stitching
The first investigation using a FE approach pointed the influence of the assembly seam on the forming of multi-ply NCF layups [5]. In a first step, an extensive mechanical material characterization was carried out. The single lap shear test was chosen to investigate the behavior of the stitched NCF plies. Also, the bias extension test was used to study the behavior of constrained assembly seams. These tests dispensed a proper characterization of the structural stitching and permitted an identification of the important parameters to bring into the simulation model. Both geometrical and mechanical characteristics of the stitches were considered. The implementation of the local stitching was then conducted by a reverse engineering approach. The study presented in this paper tends to validate these input parameters. To do so, forming of stitched multi-ply NCF layups are experimentally and virtually conducted using a double diaphragm forming process. The assessment is performed by comparing both results.
2 Forming of the composite layup
The validation of the simulation model is performed by comparing the fiber orientations extracted from the simulation with these measured experimentally after forming of a stitched double layer carbon fiber NCF layup.

2.1 Tooling
The tooling used for the validation is a generic side frame structure. Its shape can be seen in Figure 4. This geometry is interested for forming validation because of its double curvature.

2.2 Layup
The layup formed on the side frame tooling is composed of two layers: a -/+45° NCF layer at the bottom and a 0/90° NCF layer at the top. In between, two layers of binder are used. The sewing of the preform is performed with an automated machine (Fig. 5). Fig. 6, the cut-out of the preform and the stitching shape are drawn as solid and dashed lines, respectively.

2.3 Forming method
The forming method used for the validation is the double diaphragm forming process.
- The preform is firstly placed between two protective foils. These are used during forming to lower the friction with the membranes.
- Then, the whole “composite + foil” layup is placed between both membranes of the double diaphragm machine
- The membranes are then closed. Once vacuum in between the two membranes is reached, the platen, composed of the “membranes + composite + foils”, is moved upwards. At this time, the activation process can start. This step intends to soften the binder. To do so, infra-red lamps are used for a sufficient time at a temperature of 120°C. Two sensors are placed in between the membranes to monitor the temperature variations.
- The platen is lowered over the tooling and vacuum between the tooling and the platen is achieved. Soon after the forming occurs, the activation process is switched on again in order to ensure a proper activation.
- Finally, the infra-red lamps are turned off and the composite cools down to room temperature under vacuum. No external means are used to speed up the cooling down process. Then, the vacuum between the tooling and the platen is switched off, the platen is moved up and the vacuum in between the membrane is also switched off. After being removed from the tooling, the preform is taped to the tooling to avoid any distortion (Fig. 7).

3 Simulation model
The simulation model is built up using the commercially available software PAM-Crash® developed by ESI group®. This software uses a finite element approach. The solver employed for the calculations is the version 2011 of the PAM-FORM 2G Solver.
A rectangular mesh with a 10 mm side length is used. The orientation of NCF layers is ensured by the orientation of the element edges. Therefore, the ±45° layer is model by rotating the rectangular element by 45° within the global coordinate reference system.
The material model used to represent a dry carbon fiber NCF is described by the so-called MAT140, a thermo-visco-elastic matrix with an elastic fibre formulation card. Such a formulation is already validated and not assessed within this validation process.
Instead, the approach used to model the structural stitching is assessed. As described in [4], the approach using PLINK elements with a spring beam material card, referenced MAT223, is considered. The complete experimental process is modeled, except the foil used to lower the friction between membranes and composites. Instead, the friction coefficient between these is adapted within the contact cards. An overview of the simulation model can be seen in Fig. 8.

4 Measurement and validation procedures
4.1 Measurement system
The measurement of the fiber orientations is performed by an automated reproducible measuring system named EuroPAS (Eurocopter Preform Analysis System). Mounted on a robot, a high resolution camera is used to photograph the chosen areas. Since these areas cannot be covered by a single photo, several photos have to be taken and then assembled to rebuild the complete area. This
assembly is made possible by registering the coordinates of every photo by the system.

4.2 Regions under investigation
The investigations do not cover the entire frame. Only three regions are identified as interesting. The first region, located on the web of the part (Fig. 9a), is taken as reference, because fibers within this region are not expected to be much distorted during the forming process. The other two regions, located on the outer flange (Fig. 9b and 9c) are regions where waviness is likely to occur during forming due to the double curvature of the part. Measurements on the outer curvature cannot be performed because of the shape of the part (very small radius).

4.3 Validation system
Comparisons between the fiber orientations measured by the camera and those extracted from PAM-Crash® are conducted using EuroPAS. By projecting the mesh of the simulation on the assembled photo and using an optical method of edge recognition, the software can detect the most common fiber orientation per cell. This step is governed by two parameters, the minimum edges account and maximum standard deviation. Finally, the comparison is performed and can be said “good”, “fair” or “bad” depending on the user-defined tolerance thresholds.

In this work, standards and guidelines detailed by the EuroPAS developer are followed. Inputs that are validated within previous projects are used as much as possible (Table 1) [5].

5 Validation
5.1 Results
The quality of the simulation is assessed per region. Comparisons conducted between simulated and measured fiber angles are reported in Table 2.

5.2 Region 1 – Web
Measurements on the web are performed using the parameters presented in Table 1. This flat geometry is used as a reference, because fibers are not expected to be much distorted. Thus, measurements within this region enable a proper calibration of the measuring system.

As it can be seen in Table 3 and Fig. 10, the quality of the comparison is very good. More than 96% of the detected fiber orientations differed a maximum of 4° with the orientations calculated by the FE-Software PAM-Crash®. The comparison performed within region 1 shows an excellent correlation between the fiber orientations calculated by the simulation and the measured ones. This particularly shows that the measuring tool is properly calibrated.

5.3 Region 2 – Short outer flange
Measurements for region 2 are performed using the parameters presented in Table 1. The outer flange is a particular point of interest, because it is located at the vicinity of the outer curvature of the frame, where fiber re-orientations are likely to occur (Fig. 9b).

As it can be seen in Table 4 and Fig. 11, the detection of the fiber orientations is difficult, in particular for the cells located the nearest of the curvature (left side of Fig. 11). This is due to the fiber re-orientation occurring in this region. Because of the significant waviness, the fiber orientations within most of these cells cannot be detected. A finer mesh would have likely solved this issue, since smaller mesh cells would reduce the window in which the orientation should be defined.

If the undetected cells, as well as the two measurements located the nearest of the curvature (left side on Fig. 11) would not be taken into account, the results would endorse the quality of the simulation (compare Table 5 and Table 6). In this case, almost two third of the fiber orientation calculated by the simulation would have a deviation of less than 4° compared to the experimental ones. The correlations between fiber orientations measured by the optical system and these calculated by the simulation software are decent along the structural seam. Thus, the implementation of the structural stitching within the simulation software (type of element and material card) is acceptable but would need few modifications to improve the predictions within difficult areas, e.g. curved parts.

The results of the comparisons performed within region 2 are good on average for every cell in which the detection of the fiber orientation is made possible by EuroPAS. For the rest, the detection
could be enhanced for a new model with a finer mesh.

5.4 Region 3 – Long outer flange
The validation process within this region is performed using specific parameters. The parameters controlling the detection of the fiber orientations (minimum edges account and maximum standard deviation) are kept identical as these presented Table 1, but the thresholds governing the comparisons between simulated and experimental fiber orientations are loosen. The quality of the simulation within this area is indeed not good enough to keep restrictive comparison parameters. The thresholds presented in Table 7 are used instead. The long flange is, as region 2, a particular point of interest because it is located at the vicinity of the outer curvature of the frame. This part is especially interesting to challenge the accuracy of the simulation because fiber re-orientations are likely to occur (Fig. 9c).

As it can be seen in Table 8, the comparison performed by EuroPAS is satisfying: a fiber orientation is detected for 90% of the cells. As for region 2, the undetected cells are located close to the curvature (right side of Fig. 12).

Fig. 12, it can also be noticed that good correlations are more located on the left and the bottom of the picture. These are the areas further away from the curvature. By contrast, the comparisons for the cells located in the vicinity of the curvature (right side of Fig. 12) depict a majority of “fair” and “bad” correlations. This shows that the simulation is not robust enough to predict the fiber orientations when a difficult geometry is encountered.

All in all, the accuracy of the simulation is encouraging: more than 70% of the fiber orientations calculated by the simulation have a deviation of less than 16° compared to those measured by the optical system (Table 9). However, the comparison criteria are not restrictive enough to enable a proper validation.

To challenge these results, a comparison between the fiber orientations measured after forming on an experimental stitched preform and the fiber orientations extracted from a simulation using an unstitched layup is conducted. The point is to confront these results to assess the modeling of the structural stitching using a PLINK element and a spring beam material card [5].

The comparison between the fiber orientations measured on a stitched preform and these extracted from a simulation of an unstitched layup are performed using the parameters presented in Error! Reference source not found.. As it is shown Table 10, the fiber orientations of almost 80% of the cells are detected. The undetected ones are located near to the curvature (right side of Fig. 13).

Within the detected cells, the correlation between the fiber orientations after forming of an unstitched preform compared to the fiber orientations measured on an experimental formed stitched layup can be found Table 11.

Table 11 shows that only 29,70% of the cells, when fibers orientations are extracted from a simulation using an unstitched layup, have an error lower than 12° compared to fiber orientations measured on a formed stitched component. In comparison, when the analysis is performed with fiber orientations extracted from a simulated stitched preform, the results shows a correlation of 53,57% of the cells for the same threshold criteria (Table 9).

As main outcome of this comparison, the necessity to take into account the structural stitching within forming simulations is pointed out. The type of modeling using a PLINK element and a spring beam material card gives encouraging results when compared to experimental trials. It is a first step even though it cannot be validated completely. The simulation error in the prediction of the fiber orientation is larger than 10° for some regions. The model needs to be improved to increase the quality of the prediction, especially within parts of difficult geometries, e.g. regions with a significant curvature.

6 Discussion
The quality of the validation process is affected by the experimental forming step, the perspective error induced by the position of the camera, the quality of the photo assembly, the quality of the fiber orientation detection and the quality of the simulation.

6.1 Distortions due to preform removal
After forming, when the preform is removed from the tooling, some fiber re-orientations might occur. To minimize this effect, the preform is taped on the tooling.
6.2 Perspective error
Due to the geometry of the frame and the position of the camera when the pictures are taken, a perspective error on the measurements might occur. Even if it has not been accurately calculated, this error can be neglected in this study since comparisons were performed by excluding the areas located within the curved region of the frame.

6.3 Photo assembly error
As it has already been detailed within 4.1 Measurement system, a single picture cannot cover the entire region under investigation. Therefore, several pictures are taken and then assembled to rebuild the complete area. However, as it can be seen in Fig. 14, this process can be inaccurate and lead to some irregularities in the photos assembly. In this study, the assembly of the pictures is hindered by the geometry of the frame. However, this error can be neglected, because it leads to an assembly error of a few millimeters. These gaps do not bother the detection of the mean fiber orientation performed by EuroPAS since most of the orientation remains constant at the interface between two pictures.

6.4 Fiber orientation measurement error
The detection of the fiber orientation made by EuroPAS for every cell mesh is made by a numerical analysis. To do so, the software uses the pixels of the photos and detects several different orientations per cell. Then, based on a statistical approach, the most encountered value is chosen as the suitable detected fiber orientation. As it can be seen in Fig. 15, the selection of the mean fiber orientation was clear for every cell. It is represented by the red line. A detection of this quality is made possible by a good calibration of the measuring system. In this direction, the parameters referred as the minimum edges account and the maximum standard deviation (Table 1) play an important role.

6.5 Simulation error
The fiber orientations extracted from the simulation are subjected to a low error due to an incorrect input concerning the application of the vacuum between the tooling and the platen. In this study, the same value is used for the simulation of the stitched and unstitched preforms. However, it is noticed that with a stitched preform, the compliance of the preform to the tooling is not optimal. This might be explained by the PLINK elements used to model the structural stitching that create a bit of resistance to deformation.

7 Conclusion
The validation of the implementation of the local stitching in forming simulations is carried out on a helicopter generic side frame structure. The validation process is performed by comparing the fiber orientations extracted from the simulation and these measured by an optical system on an experimentally formed layup. The analyzing tool used is EuroPAS. The implementation using a PLINK element combined with a spring beam material card gives encouraging results even though it cannot be validated yet. The deviations between the simulated results and the measurement performed on the experimental part are too large (greater than 10° for some regions). However, it is a first step to take into account the influence of the structural stitching within forming simulations. The robustness of the model needs to be improved since the predictions of the simulation are still inaccurate for parts with difficult geometries, e.g. curved parts. To be fully validated, the model must be reworked, and the errors due to the measuring system (perspective of the camera, assembly of the photos etc.) must be lowered.

With the draping simulation based on FEM it is possible to gain a better understanding of the draping behavior of dry stitched carbon fibre NCF ply stacks. From these results, the optimized stitching locations and stitching patterns can be determined such that the influence of the stitching on the forming is minimized.

Acknowledgement
The work reported in this paper has been partly carried out in the framework of M.A.I Design, a project funded by the German Federal Ministry of Education and Research (BMBF) which is gratefully acknowledged.
**Fig. 1.** NCF ply stack with local stitching.

**Fig. 2.** Test setup of a lap shear test, side view.

**Fig. 3.** Top view of draping results over a hemisphere with a 2-ply stack. Shear angle distribution is given for non-stitched ply stack and stitched ply stack (along red dashed line).

**Fig. 4.** Helicopter generic side frame.

**Fig. 5.** Layup of the preform.

**Fig. 6.** Stitching and cut-out lines.

**Fig. 7.** Preform taped over the tooling.

**Fig. 8.** Overview of the simulation model.
Fig. 9. Regions under investigation (a) region 1 - web (b) region 2 - short outer flange (c) region 3 - long outer flange.

Fig. 10. Region 1 - Comparison between simulated and measured fiber orientations.

Fig. 11. Region 2 – Comparison between simulated and measured fiber orientations.

Fig. 12. Region 3 - Comparison between simulated and measured fiber orientations.

Fig. 13. Region 3 - Comparison between fiber orientations extracted from an unstitched simulated preform and those measured on a stitched one.

Fig. 14. Inaccurate photo assembly.

Fig. 15. Histogram – detection of the fiber orientation.

<table>
<thead>
<tr>
<th>Minimum edges account</th>
<th>Maximum standard deviation</th>
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<tbody>
<tr>
<td>50%</td>
<td>40</td>
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</table>

<table>
<thead>
<tr>
<th>Good correlation [°]</th>
<th>Fair correlation [°]</th>
<th>Bad correlation [°]</th>
</tr>
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<tr>
<td>X &lt; 4°</td>
<td>4° &lt; X &lt; 8°</td>
<td>X &gt; 8°</td>
</tr>
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Table 1. Input defined within EuroPAS.
Table 2. EuroPAS evaluation results – difference between measured and simulated results.

<table>
<thead>
<tr>
<th>Layup</th>
<th>Part</th>
<th>Average angle difference [°]</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0/90 // -/+45]</td>
<td>Region 1</td>
<td>1.89</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>Region 2</td>
<td>4.7</td>
<td>5.28</td>
</tr>
<tr>
<td></td>
<td>Region 3</td>
<td>13.15</td>
<td>6.85</td>
</tr>
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</table>

Table 3. Region 1 - Ratio of detected (good, fair and bad) and undetected cells.

<table>
<thead>
<tr>
<th>Good correlation [%]</th>
<th>Fair correlation [%]</th>
<th>Bad correlation [%]</th>
<th>Undetected [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>96,06</td>
<td>3,94</td>
<td>0</td>
<td>0</td>
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</tbody>
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Table 4. Region 2 - Ratio of detected and undetected cells.

<table>
<thead>
<tr>
<th>Detected cells [%]</th>
<th>Undetected cells [%]</th>
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<tbody>
<tr>
<td>54,95</td>
<td>45,05</td>
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Table 5. Region 2 - Average fiber orientation difference and standard deviation within the detected cells.

<table>
<thead>
<tr>
<th>Region 2 – Detected cells</th>
<th>Average angle difference [°]</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.82</td>
<td>2.96</td>
</tr>
</tbody>
</table>

Table 6. Region 2 - Ratio of good, fair and bad correlations within the detected cells.

<table>
<thead>
<tr>
<th>Good correlation [%]</th>
<th>Fair correlation [%]</th>
<th>Bad correlation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>62</td>
<td>24</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 7. Input defined in EuroPAS for region 3.

<table>
<thead>
<tr>
<th>Good correlation [°]</th>
<th>Fair correlation [°]</th>
<th>Bad correlation [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>X &lt; 12°</td>
<td>12° &lt; X &lt; 16°</td>
<td>X &gt; 16°</td>
</tr>
</tbody>
</table>

Table 8. Region 3 - Ratio of detected and undetected cells.

<table>
<thead>
<tr>
<th>Detected cells [%]</th>
<th>Undetected cells [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>89,60</td>
<td>10,40</td>
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Table 9. Region 3 - Ratio of good, fair and bad correlations within the detected cells.

<table>
<thead>
<tr>
<th>Good correlation [%]</th>
<th>Fair correlation [%]</th>
<th>Bad correlation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>53,57</td>
<td>18,75</td>
<td>27,68</td>
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</table>

Table 10. Region 3 - Ratio of detected and undetected cells (comparison with unstitched model).

<table>
<thead>
<tr>
<th>Detected cells [%]</th>
<th>Undetected cells [%]</th>
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<tbody>
<tr>
<td>78,91</td>
<td>21,09</td>
</tr>
</tbody>
</table>

Table 11. Region 3 - Ratio of good, fair and bad correlations within the detected cells (comparison with unstitched model).

<table>
<thead>
<tr>
<th>Good correlation [%]</th>
<th>Fair correlation [%]</th>
<th>Bad correlation [%]</th>
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<tbody>
<tr>
<td>29,70</td>
<td>35,64</td>
<td>34,65</td>
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References


