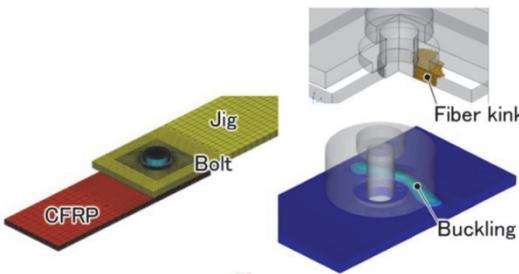


# Numerical Simulation Technology by Damage Modeling in Mechanically-fastened Composite Joints under Combined Loads

RYOSUKE HASHIZUME<sup>\*1</sup> YUYA NAGATOMO<sup>\*2</sup>YUKIHIRO SATO<sup>\*1</sup>MASAYOSHI SUHARA<sup>\*1</sup>KOJI ESAKI<sup>\*3</sup>TAKAYUKI SHIMIZU<sup>\*3</sup>

When applying composites such as fiber reinforced plastics (FRP) in product structures, challenges lie in the necessity of conducting many tests to ensure the structural reliability and the consequent prolonged period of time required for development. Mitsubishi Heavy Industries, Ltd. (MHI) has therefore worked on the development of simulation technology to predict the strength with high accuracy, by enabling the complexities of damage in composites to be represented in numerical analysis and simulating the damage progression in sequence. This report focuses on mechanically-fastened joints, the strength of which has been difficult to predict in advance because of their complex loading conditions and various modes of failure. By analyzing how damage was initiated and developed, we assessed/compared the results with those of the structural element test and internal inspection.

## 1. Introduction

Because of their high specific strength, high specific stiffness and high fatigue and corrosion resistance, composites such as carbon fiber reinforced plastics (CFRP) are often adopted as materials for the primary structure components of aerospace vehicle to reduce the weight of the structure. In recent years, composites have also been used in automobiles, although limited to certain types of vehicles such as luxury cars and sports cars.

One bottleneck for application of composite structures is the necessity of conducting a very large number of qualification tests to ensure conformity with the high reliability requirements for products such as aerospace vehicle. This is because composites show a strong anisotropy in mechanical properties such as strength and elastic modulus and exhibit complexly varying dominant modes of failure, depending on the combination of dissimilar materials of reinforcing fiber and matrix resin.

Under such circumstances, projects are under way around the world to enable “virtual testing”, by which numerical simulation is used to replace as many development tests as possible. MHI has also worked on research and development for its application to product development<sup>(1)(2)</sup>.

This report focuses on mechanically-fastened joints such as bolts and rivets. Their joint strength and dominant mode of failure change in a complex manner with design factors such as loading conditions, environmental conditions, laminate configuration and thickness and are therefore difficult to predict in advance. As a result, the number of tests required naturally tends to increase. In the following chapters, we present our simulations for these mechanically-fastened joints<sup>(3)(4)</sup>.

## 2. Damage modeling technology in mechanically-fastened composite joints

### 2.1 Failure modes of mechanically-fastened composite joints

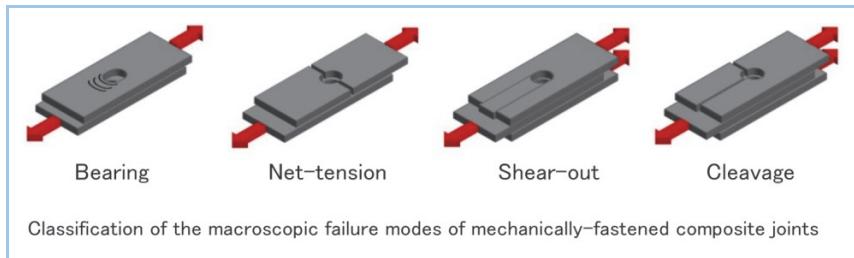
Macroscopic failure modes of mechanically-fastened composite joints are classified as shown in **Figure 1**<sup>(5)</sup>. When the bearing load which is contact pressure load at the interface between the mechanical joint and the composite and the bypass load transferred through the composite itself are applied in a combined manner, the static failure load varies depending on the degree of each of these

\*1 Strength Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

\*2 Manufacturing Technology Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

\*3 Chief Staff Researcher, Strength Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

acting stresses. Therefore, it is necessary to obtain data on the strength by testing under such combined loading conditions.



**Figure 1 Failure modes of mechanically-fastened composite joints<sup>(5)</sup>**

## 2.2 Damage modeling technology overview

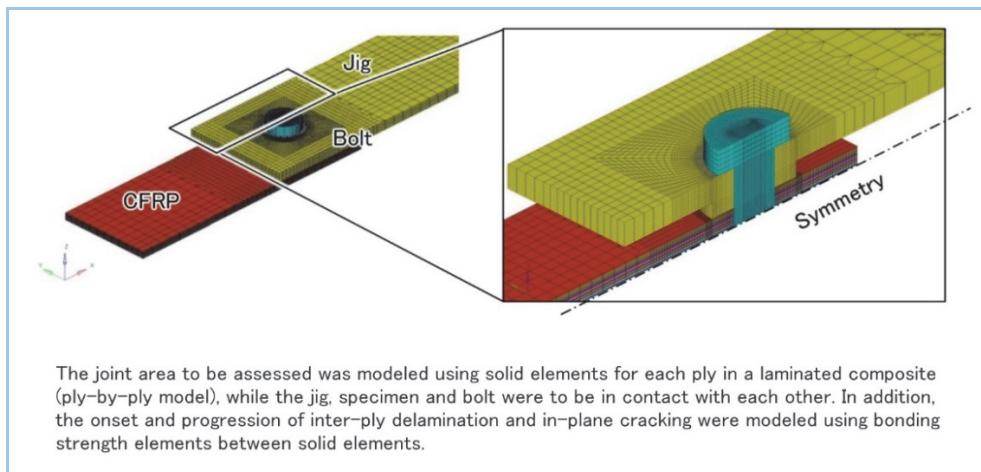
In damage modeling technology for composites, the nonlinear finite element method is used to predict the macroscopic failure behavior and strength, by modeling the behavior of microscopic damage at its onset and progression in the composite failure process according to the constitutive law of the element of each ply in a laminated composite and the element interfaces.

Firstly, regarding the inside of the element, microscopic damage such as fiber fracture, fiber kinking and matrix cracking is predicted by the failure criteria called LaRC (developed mainly by NASA Langley Research Center). The softening behavior is modeled considering energy dissipation during damage progression based on continuum damage mechanics (CDM)<sup>(6)</sup>.

In-plane cracking such as inter-ply delamination and splitting, which occurs and develops along the direction of reinforcing fiber, is modeled with Cohesive Zone Elements (CZE) as cracks occurring and developing at the element interfaces<sup>(7)</sup>.

## 2.3 Analysis model

**Figure 2** gives the analysis model. Using Abaqus, a commercial finite element solver, the assessment area of each ply in a specimen is divided into solid elements, while the jig, bolt and specimen are to be in contact with one another. The occurring and developing behavior of microscopic damage in the element was analyzed by incorporating our original code as a user subroutine.



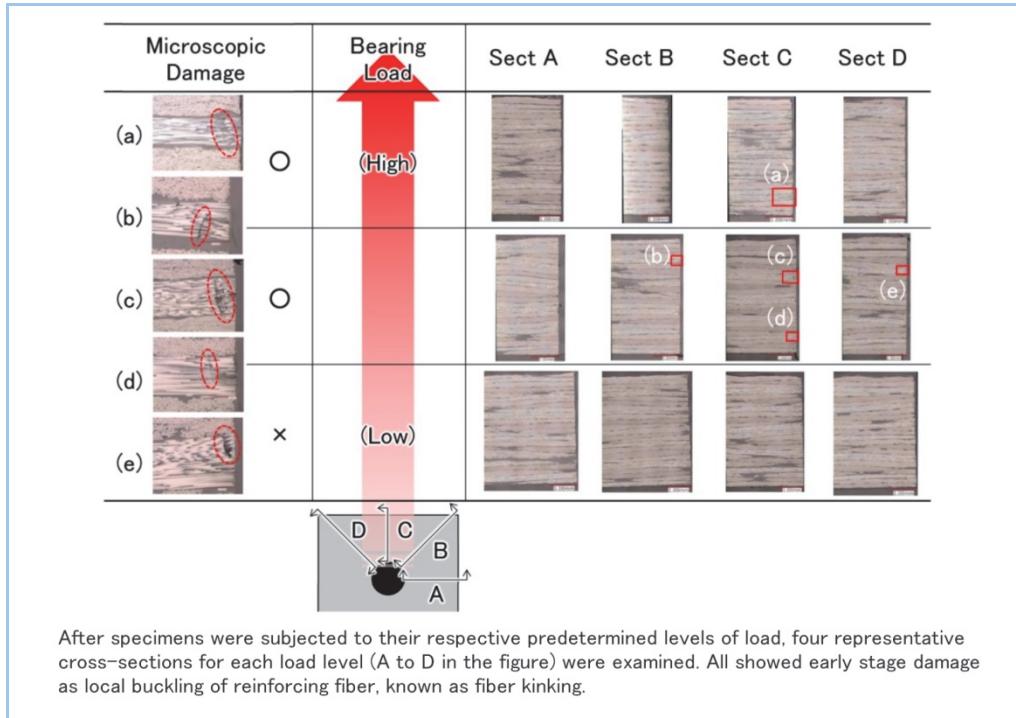
**Figure 2 Analysis model**

## 3. Comparison of results between damage simulation and structural element test

### 3.1 Damage initiation comparison

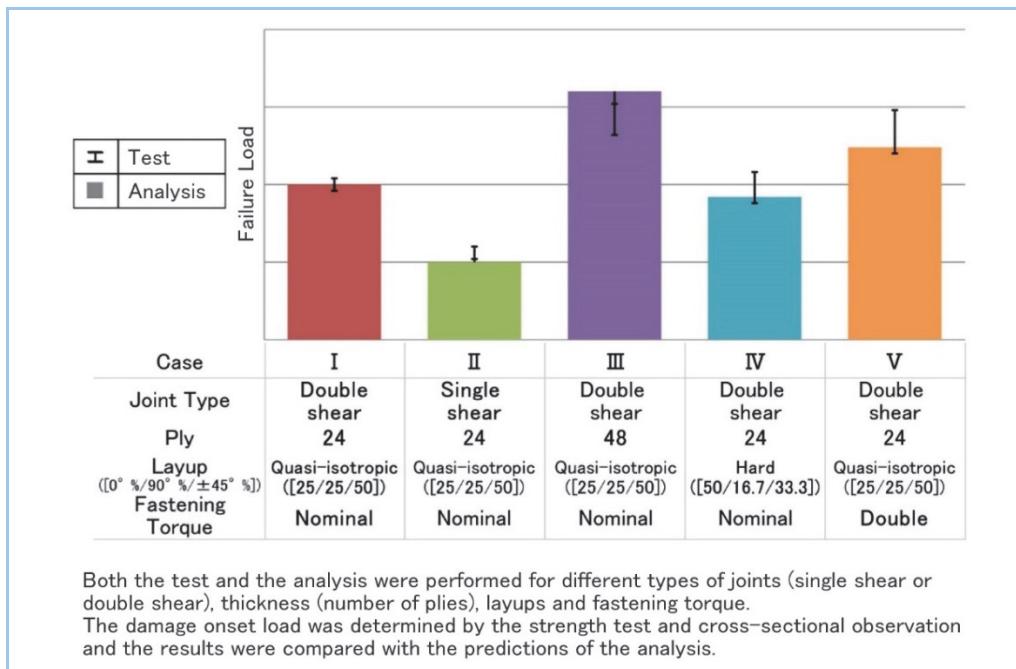
The structural element test and internal inspection were carried out to compare the occurrence of damage. Specifically, five types of specimens with varying stacking sequence, thickness, etc., were subjected to different levels of maximum tensile load before being unloaded. The specimens were then removed to observe their cross-sections by X-ray CT and optical microscope and characterize the load at which microscopic damage was initiated. The results were compared with the predictions of the analysis.

Given as an example in **Figure 3** are the results of cross-sectional observation for a 24-ply quasi-isotropic laminate, which is considered as the reference case in this test. The cross-sectional images shown herein correspond to the three levels of maximum tensile load. Those at the bottom row are of a specimen with the lowest applied load, showing no occurrence of damage. On the other hand, the images at the middle and upper rows, which are of specimens subjected to higher levels of load, indicate the presence of damage in the form of fiber kinking. Therefore, it can be considered that damage was occurred at a certain level of load between the bottom and the middle rows.



**Figure 3 Example of cross-sectional observation images**

In this way, the level of load at which damage is initiated was characterized for each type of the specimens. The results were shown in **Figure 4**, together with the predictions of the analysis. The lower bound of the error bar represents the maximum value of the load at which no damage was observed in the cross-sections, while the upper bound represents the minimum value of the load at which damage was observed. Although there are some variations depending on the type of specimen, it has been confirmed that the predictions are generally in good agreement with the test results.

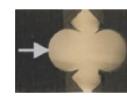
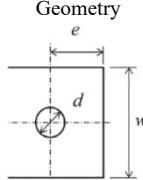


**Figure 4 Damage onset analysis and the test results**

### 3.2 Comparison of damage developing behavior

This section presents the results of a comparison of damage developing behavior. Specifically, the results of failure mode simulation are compared with those of the structural element test. It has been reported that mechanically-fastened composite joints exhibit macroscopically different modes of failure when the dimensions of the specimen change<sup>(8)</sup>. Using specimens with the geometrical configuration listed in **Table 1**, we compared both results and confirmed that the analysis can predict the change in the dominant failure mode.

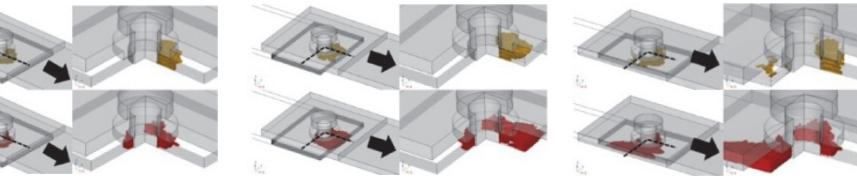
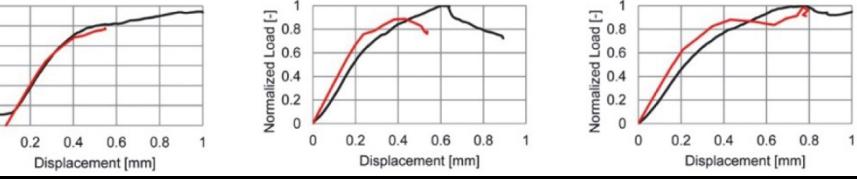
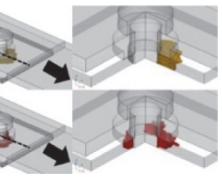
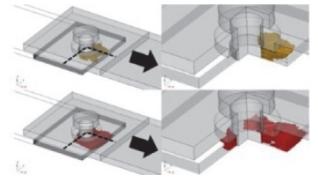
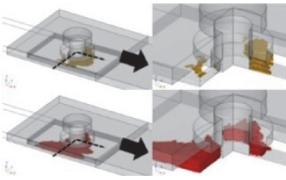
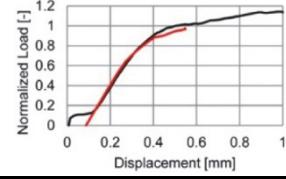
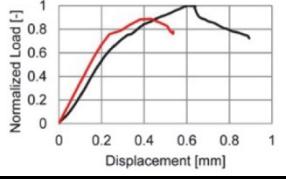
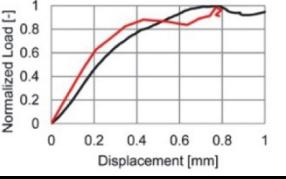
**Table 1 List of specimen configurations for both analysis and testing to confirm change in failure mode**

Failure Mode <sup>(8)</sup>	Bearing	Shear-out	Net-tension
			
Geometry 			
w/d	5	5	3
e/d	2.5	1.5	2.5

The dimensions of the specimen were set with the expectation that each would exhibit the corresponding failure fracture mode as noted in the upper row.

**Table 2** compares the results between the testing and the analysis. The analysis results successfully predicted the change in the dominant failure mode shown in the test and the predicted failure loads were also within  $\pm 15\%$  of those obtained by the test. Fiber kinking was the main damage mechanism under the conditions in which bearing is the dominant failure mode. On the other hand, as the distance between the hole in the specimen and the free edge (indicated as e in the table) or the width of the specimen (w in the table) became smaller, matrix cracking became the prevailing damage mechanism. The dominant failure mode was changed accordingly to shear-out (in the case of smaller e values) or net-tension (smaller w values), which was indicated by both the test and the analysis. Furthermore, both results also showed the lowering of the load in these cases, which was caused by the matrix crack having originated from the edge of the hole and developed until they reached the free edge.

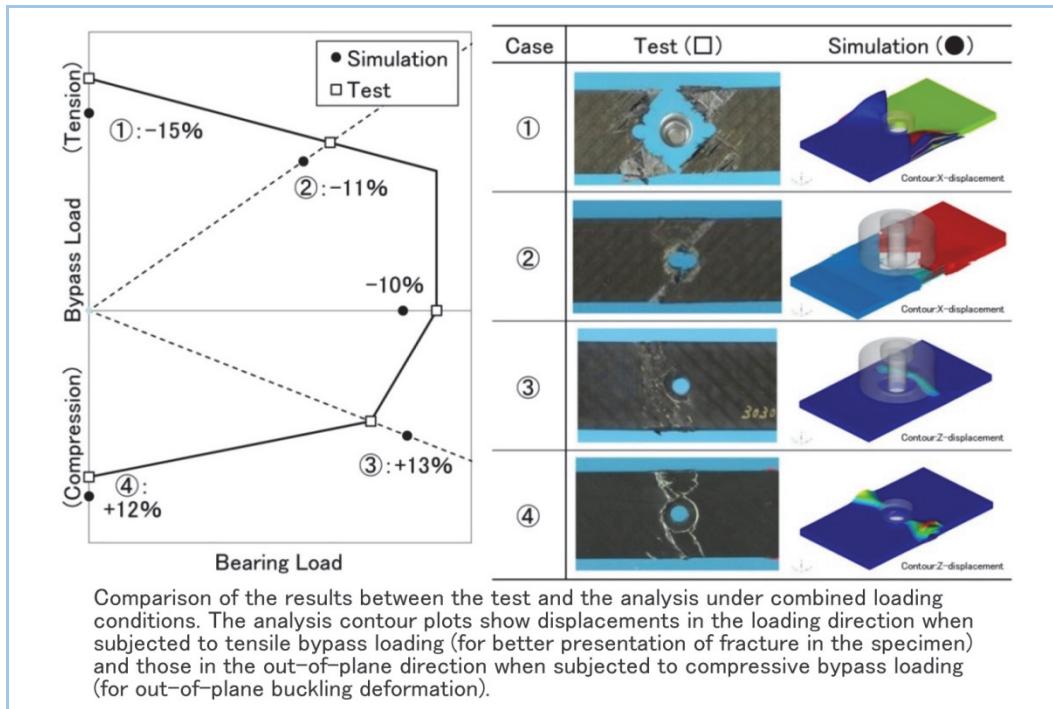
**Table 2 Comparison of test and analysis results to confirm change in failure mode**

	Bearing	Shear-out	Net-tension
			
Simulation ■: Kink ■: Matrix cracking			
Load-Displacement —: Test —: Simulation			

The damage progression results of the test and the analysis to confirm the relationship between the onset/progression of microscopic damage and the macroscopic failure mode. Regarding the analysis results, the elements damaged by fiber kinking are colored in yellow (■), while those damaged by matrix cracking are in red (■).

### 3.3 Comparison of failure load predictions

Lastly, **Figure 5** presents the accuracy validation results for strength prediction under combined loading conditions. The figure also includes the failure modes obtained by analysis under the loading conditions other than in Table 2 (which is bearing load only). As comparison results, the simulated failure loads are within approximately  $\pm 15\%$  of the test results. It has therefore been confirmed that the test results and the analysis predictions are correlated with each other in terms of failure mode. Especially when subjected to combined loads of bearing and compressive bypass, the location of local buckling caused by the developing of microscopic damage and inter-ply delamination is different from that occurring under the load of compressive bypass only. This phenomenon was also successfully reproduced by simulation.



**Figure 5 Strength prediction results under combined loading conditions**

## 4. Conclusion

This report pertains to the development of simulation technology to accurately predict the strength by modeling in detail the occurrence and developing behavior of microscopic damage in composites, presenting an example case of mechanical joints that can exhibit a variety of failure modes depending on the loading conditions. We will promote the use of such simulation technologies to ease the burden of conducting many development tests, reduce product costs and shorten the period of time required for development. It can also be considered that proceeding effectively with the detailed damage risk assessment and the measures from the early stages of product design will contribute to improving product value, for example, in terms of enhanced reliability and a reduction in the structure weight.

Looking forward, we will further improve this simulation technology and expand its applicability by employing it not only in mechanical joints, but also in various other cases ranging from structural element testing to component testing, while validate the prediction accuracy and reliability.

## References

- (1) Yukihiko Sato, et. al, Strength Prediction Technology for Composite Materials Simulating Damage Phenomena, Mitsubishi Heavy Industries Technical Review, Vol.55 No.2 (2018)
- (2) Sato, Y. et al., Progressive failure analysis for impact damage and compressive strength of composite laminates, Mechanical Engineering Journal, Vol.4 No.5 (2017) p.16-00710
- (3) Ryosuke Hashizume, et. al, The Study on Predicting the Kink Onset Load in Mechanically Fastened Composite Joint, #9 Japan Composite on Conference Material, (JCCM-9), Proceedings 2B-04 (2018) p.1
- (4) Ryosuke Hashizume, et. al, Development of the damage progression FEA method for CFRP bolted joints, #10 Japan Composite on Conference Material, (JCCM-10), Proceedings 2C-04 (2019) p.1
- (5) Composites UK Ltd, JOINING OF FIBRE-REINFORCED PLYMER COMPOSITES – A Good Practice Guide, (2020)
- (6) Pinho, S.T. et al., Material and structural response of polymer-matrix fibre-reinforced composites, Journal of Composite Material, Vol.46 (2012) p.2313-2341
- (7) Hallet, S.R. et al., The open hole tensile test: a challenge for virtual testing of composites, International Journal of Fracture, Vol.158 (2009) p.169-181
- (8) P.P.Camanho et al., A design methodology for mechanically fastened joints in laminated composite materials, Composite Science and Technology, Vol.66 (2006) p.3004-3020