# A STUDY ON VIRTUAL TESTING OF COMPOSITE BOLTED JOINTS BY DAMAGE MODELING

Ryosuke Hashizume[1], Yuya Nagatomo[2], Yukihiro Sato[3],
Masayoshi Suhara[4], Kouji Esaki[5], Takayuki Shimizu[6]

[1-6] Research & Innovation Center, Mitsubishi Heavy Industries, Ltd., Nagoya, Japan
[1] ryosuke.hashizume.k8@mhi.com
[2] yuya.nagatomo.8v@mhi.com
[3] yukihiro.sato.hw@mhi.com
[4] masayoshi.suhara.t8@mhi.com
[5] kouji.esaki.38@mhi.com
[6] takayuki.shimizu.s2@mhi.com

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## ABSTRACT

A lot of tests are required in conformity with building block approach for design and certification of composite airframes. Especially, composite bolted joints show so various failure modes, that failure loads are difficult to predict. These days, high-fidelity simulation with damage modeling can probably be an alternative of real testing, as virtual testing. In this study, the applicability of Continuum Damage Mechanics (CDM) and Cohesive Zone Models (CZM) was confirmed to simulate onset, progression and mutual interaction of any kinds of damages in composite bolted joints. Simulation results for damage onset, macroscopic failure modes and failure load under simultaneous bearing-bypass loading were evaluated through the comparison with test and inspection data. This modeling technique was concluded to predict failure modes and loads within +/-15% for composite bolted specimens with various configurations and a promising to realize test reduction and virtual testing.

## 1 INTRODUCTION

So many tests are required in conformity with building block approach for design and certification of composite airframes [1], that reducing test cases would save cost and time dramatically. Above all, composite bolted joints show various failure modes [1], and failure loads are difficult to predict [2]. For example, about one third of certification tests for a commercial aircraft's composite empennage were related to bolted joints [3].

A possible reason is that design criteria of bolted joints are based on design chart called bearing-bypass interaction curve, drawn by plotting design allowables. Therefore, a large number of specimens are necessary to qualify these allowables' variability with respect to such design parameters as thickness, layup, fastener diameter and so on.

These days, high-fidelity simulation with damage modeling can probably be an alternative of real testing, so sometimes called as virtual testing [4]-[8]. In this study, applicability of modeling method with Continuum Damage Mechanics (CDM) and Cohesive Zone Models (CZM) [4]-[6] to composite bolted joints was confirmed by comparison with test and inspection data.

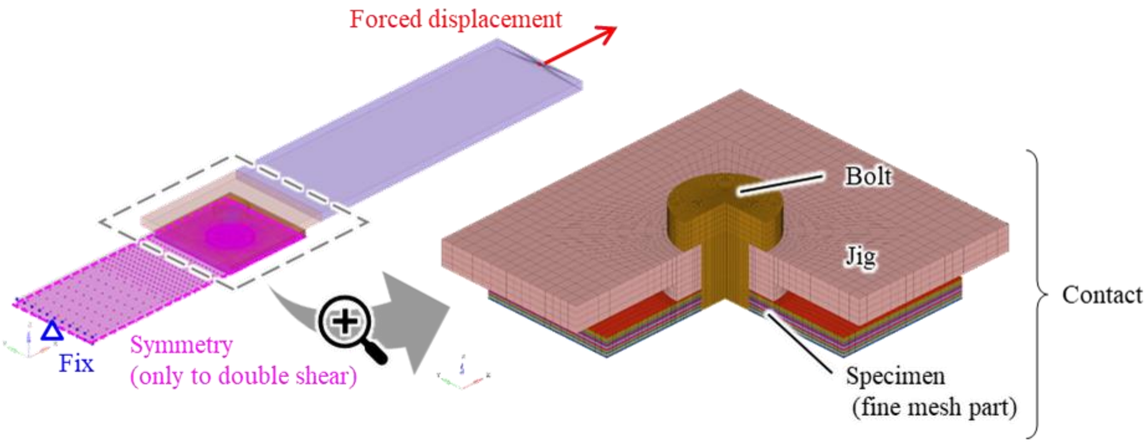



Figure 1 : An example finite element model for CDM

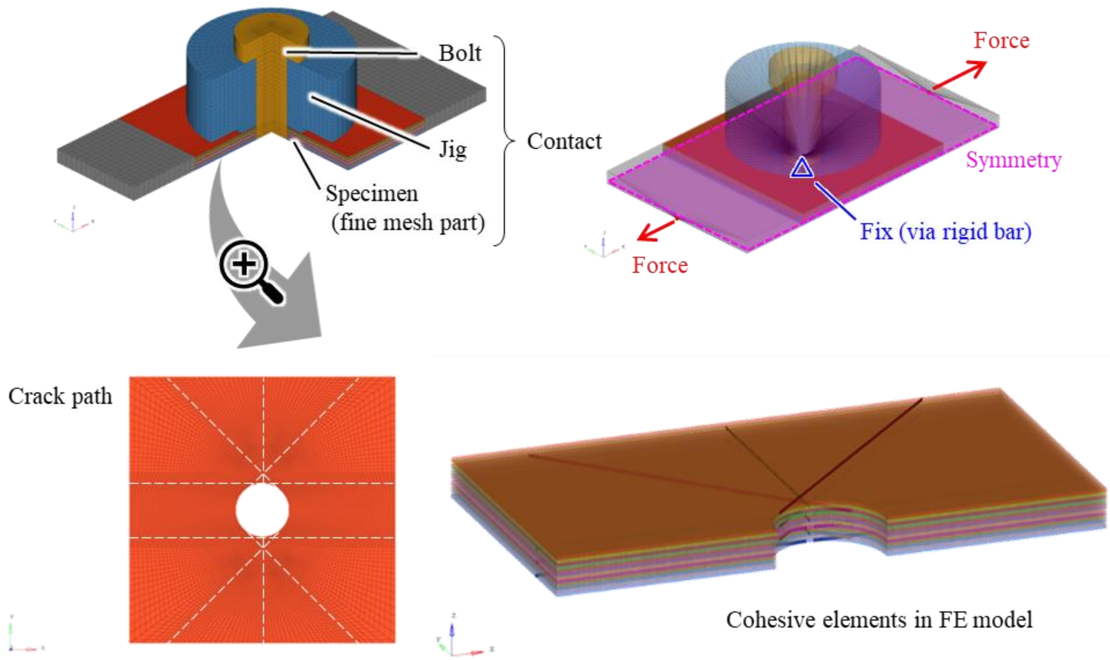



Figure 2 : An example finite element model for CZM

## 2 DAMAGE MODEILNG

### 2.1 Test specifications of bolted joints

Basic condition of specimens, testing method and procedure are summarized as follows. Specimens were fabricated by resin transfer molding with quasi-isotropic CFRP laminates for generic aerospace use. A titanium alloy fastener of 6.35 mm (1/4 in.) diameter was installed in the center of specimens, located from the edge in the distance of 2.5 times of diameter (2.5D). Then they were tested by electromechanical universal testing system at room temperature and ambient humidity, in accordance with ASTM test standards [9]-[10]. Despite the above explanation, variation was admissible for the individual test purpose, for example, joint types whether double shear or single shear, geometry of specimens, layups, fastening torques, etc.

### 2.2 Simulation models

FE model such as Figure 1 was prepared as a ply-by-ply solid elements considering the symmetricity of double shear joints, and material properties were assigned to each ply. The only case of full modeling was a single shear joint specimen because of its asymmetry. As a common modeling policy, mesh size of detailed modeling part is approximately 0.2 mm, and connected to the coarse mesh zones with tying. The mesh connectivity among specimens, bolts and jigs was isolated and provided with surface-to-surface contact.

Failure initiation in bolted joints is accompanied with microscopic damages, so failure modes in bolted joints were simulated with Abaqus, using different 2 kinds of modeling methods. Simultaneous damages, such as fiber fractures, kinks and matrix cracks, were modeled by CDM with a combination of LaRC as failure criteria [5], and implemented by user subroutine in Abaqus UMAT/VUMAT[11]. In addition, discrete damages like delaminations and intralaminar splits were modeled by cohesive elements by the built-in property definition as Figure 2.

## 3 RESULTS AND DISCUSSION

### 3.1 Characterization of bearing damage onset

Firstly, damage onset loads were characterized by destructive inspection of loaded and unloaded specimens. Specimens with different joint types, layups, fastening torque were tested and inspected with digital microscope. Then, damage onset loads were estimated by the failure index distributions computed with UMAT.

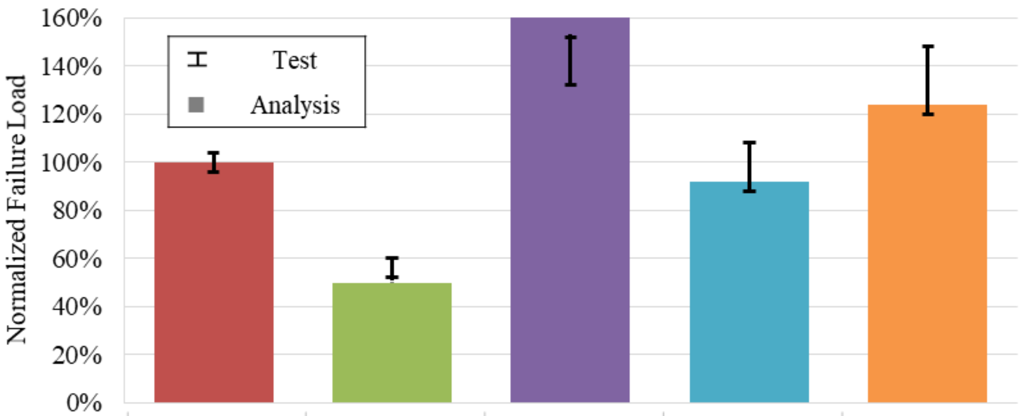
Figure 3 shows the characterized and simulated damage onset loads of all conducted cases. Failure loads are normalized by the simulated damage onset load of case I as a reference case. In this bar chart, lower bounds stand for applied test loads at which no damages were inspected. On the other hand, upper bounds represent test loads with damages observed. Damage onset loads determined by test and inspection were simulated well, and trends agreed well that their dominant micro-scale damage was kink.

Figure 4 is an instance of damage onset characterization for case I. This figure indicates that fiber kink was a dominant type of microscopic damages and estimated to onset at the load level between middle and bottom rows.

### 3.2 Failure mode variation under bearing load

The next step is to correlate failure modes with progressive failure analyses. Tensile loads were applied to specimens with different widths and edge distances in the bearing test fixture. CDM was incorporated into every FE model tabulated in Table 1 by VUMAT, but CZM was not. Then, numerical and visual damage progression behaviors were evaluated.

Generally, failure modes macroscopically observed coincided with estimation by damage growth in simulation, as shown in Table 2. Specimens with nominal geometry failed in bearing mode, and kinks were found dominant both numerically and visually. However, specimens with narrow width and short edge distance failed in net-tension and shear-out, respectively. In these specimens, matrix cracks were more dominant than the nominal specimen, and damages spread fully toward free edges.




| Case | I | II | III | IV | V |
|---|---|---|---|---|---|
| Joint Type | **Double shear** | **Single shear** | Double shear | Double shear | Double shear |
| Plies | **24** | 24 | **48** | 24 | 24 |
| Layup ([0° %/90° %/±45° %]) | **Quasi-isotropic ([25/25/50])** | Quasi-isotropic ([25/25/50]) | Quasi-isotropic ([25/25/50]) | **Hard ([50/16.7/33.3])** | Quasi-isotropic ([25/25/50]) |
| Fastening Torque | **Nominal** | Nominal | Nominal | Nominal | **Double** |

Figure 3 : Comparison between simulation and test for bearing damage onset loads

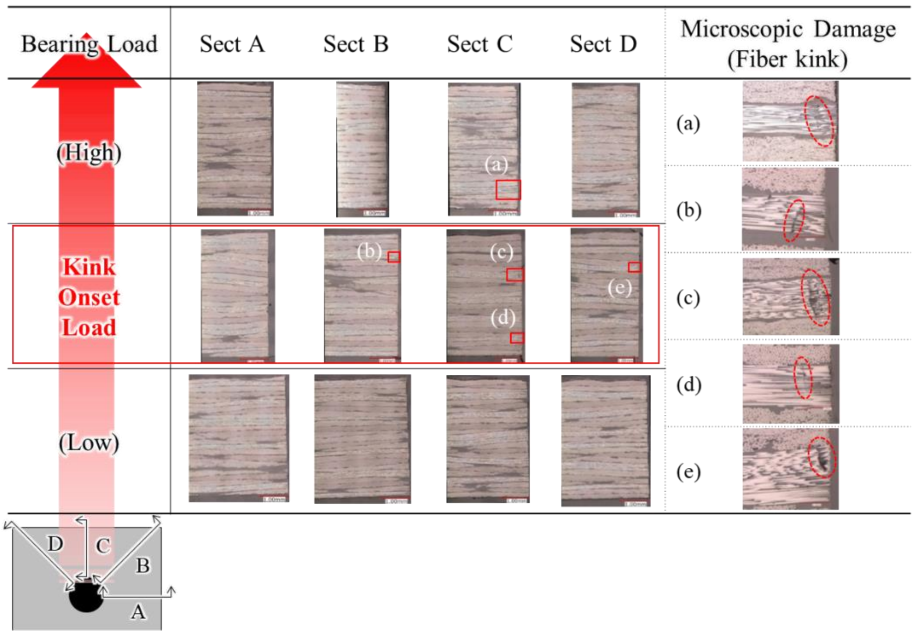



Figure 4 : Characterization of damage onset load by digital microscope inspection (Case I)

Table 1 : Geometry of FE models and their supposed failure modes

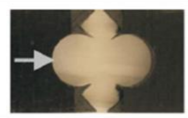
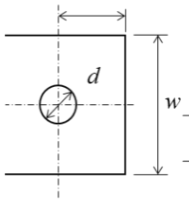
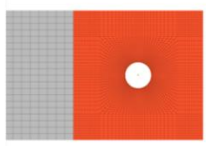
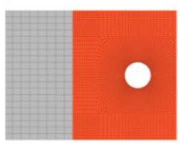
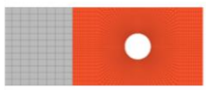
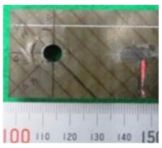
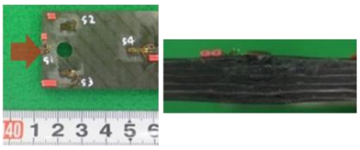
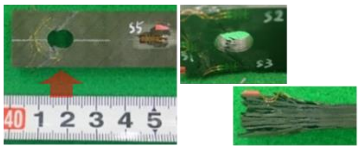
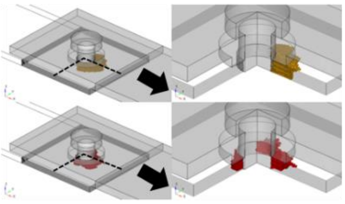
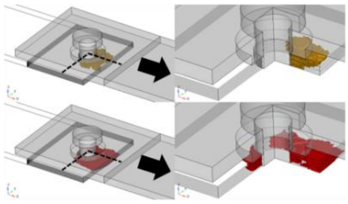
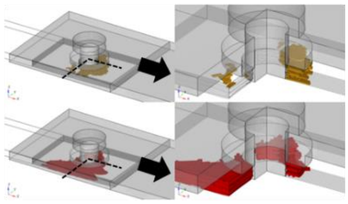
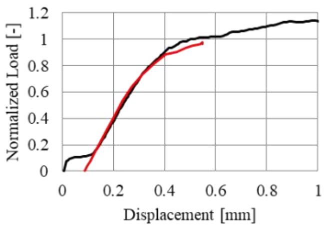
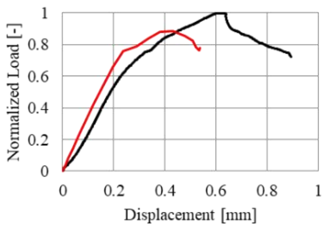
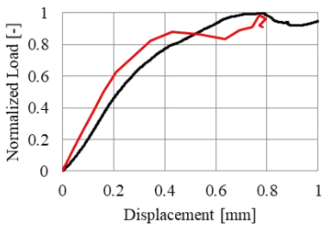
| | | Bearing | Shear-out | Net-tension |
|---|---|---|---|---|
| Failure Modes | |  |  |  |
| Geometry   | FE Model |  |  |  |
| | *w*/*d* | 5 | 5 | 3 |
| | *e*/*d* | 2.5 | 1.5 | 2.5 |

Table 2 : Macroscopic failure mode variation correlated with damage progression in simulation

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

### 3.3 Prediction error evaluation on bearing-bypass curve

As a final step of this study, prediction error of failure loads was confirmed. In addition to CDM modeling by VUMAT, delaminations and splits were modeled by cohesive elements.

Figure 5 illustrates the prediction errors were within +/-15%, compared with test data of 5 loading cases. In the simultaneous bearing-bypass loading cases, test was conducted according to the method proposed by Crews and Naik [12].

In the cases under tensile bypass loads, interaction between splits and delaminations is found to play an important role to simulate failure modes and loads. On the other hand, in compressive bypass loading cases, how kinks onset and progress was vital for subsequent delaminations and local buckling, apparent from failed specimens.

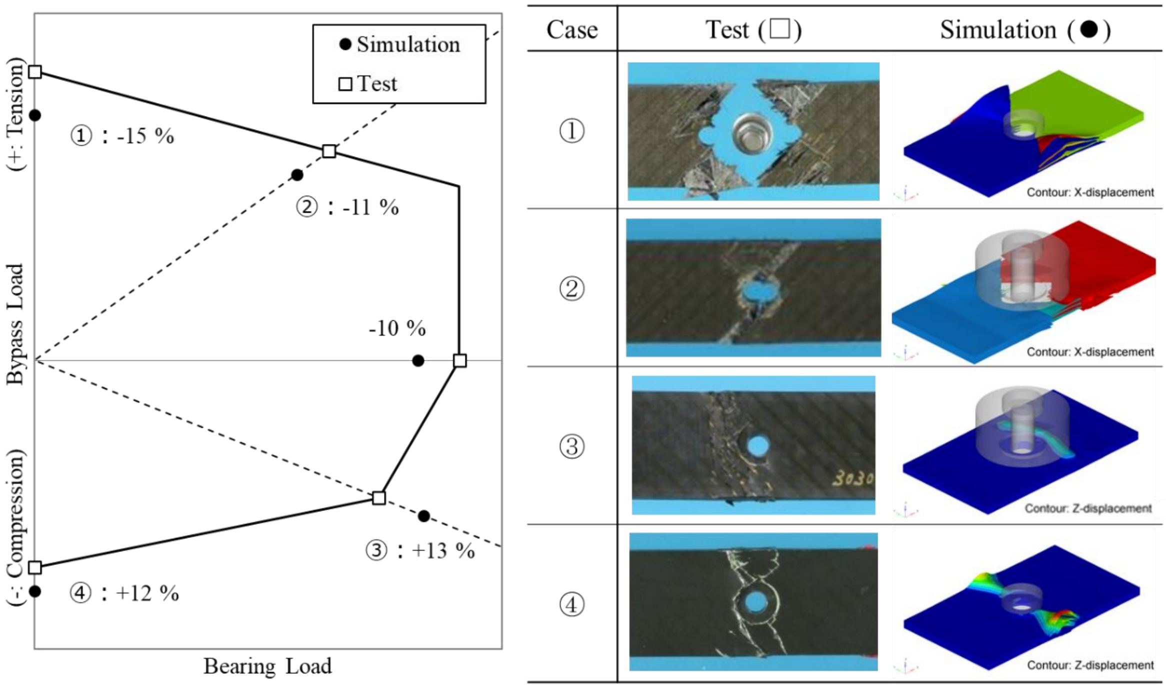



Figure 5 : Prediction error evaluation of each plot on bearing-bypass interaction curve.

## 4 CONCLUSIONS

In this study, the combination of CDM and CZM was applied to damage modeling for composite bolted joints testing. It proved to be an important role how microscopic damages onset, progress and interact mutually, when simulating failure modes and loads. It was demonstrated that macroscopic failure modes were well simulated and failure loads were predicted within +/-15%, for several kinds of bolted joint testing configurations.

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