NUMERICAL ANALYSIS OF IMPACT AND POST-IMPACT BEHAVIOR OF TITANIUM MATRIX COMPOSITES FOR LANDING GEAR APPLICATION

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Abstract

In this paper, application of titanium matrix composites (TMC) is considered as a candidate material to develop a light-weight, compact and corrosion-resistive landing gear structures. As the composite landing gear structure requires consideration the damage tolerant consideration (e.g. foreign object imapct), the present paper presents experimental and numerical programs of SiC/Ti composites taking the impact and post-impact damage and mechanical behavior into account. Low-velocity and high-velocity impact tests are performed to SiC/Ti composites, and the impact damages are characterized. Post-impact compressive tests are also conducted. A numerical finite element model is developed considering the representative damage and inelastic behaviors, and impact damage and post-impact response are simulated and compared with experimental results.

1. Introduction

Aircraft landing gear components generally occupy about 4% of the entire weight of aircraft, although they are not used during the flight. Current landing gear structures are mainly made of high strength steel (e.g. 300M [1]). Corrosion and fatigue problems of such materials may occur in service, which result in increase in cost and labor to control the manufacturing quality and maintenance program. Therefore, new types of landing gear structures are demanded to avoid the above-mentioned problems. One of the feasible candidate to replace high strength steel is carbon fiber-reinforced plastic (CFRP) composite with high specific stiffness and strength. Our preliminary study [2] indicates that application of CFRP to landing gear results in increase of the volume of landing gear components, which may induce the weight of the total aircraft. In addition, very thick CFRPs with complex shapes are required for landing gear components. This means that low bearing strength, manufacturing technique, and inspection problem of CFRPs are to be solved for the real application. Consequently, our previous study concludes that CFRP components are not generally suitable for landing gear structures except for the large aircraft. Light-weight and compact landing gear components are to be developed.

In this paper, application of titanium matrix composites (TMC), specifically SiC-fiber/Titanium composites, is considered as an alternative candidate material for landing gear structures. SiC/Ti composites exhibit similar specific stiffness to CFRPs, and have high corrosion resistance and lightening-strike resistance. Landing gear structures are possibly subjected to foreign object impacts (e.g. birds, stones on the ground, tools and bolts, etc.), and damage tolerant consideration is required [3]. In addition, virtual testing technology is necessary to avoid the cost/labor increase in the design and the certification procedures. This paper aims to investigate the impact damages and post-impact behavior of SiC/Ti composites experimentally, and develop a simple numerical model to predict the impact damage and the residual strength of SiC/Ti composites.

2. Experimental

In the present study, SiC fiber/titanium matrix unidirectional composites are of interest for landing gear application. This is because landing gear structures are mainly subject to uniaxial compression and tension, and titanium matrix is considered to be enough stiff to maintain the stability against the compression. Several kinds of TMC plates are prepared to investigate the basic mechanical properties and the damage behavior under transverse impact loads. The followings sections describe the material used, low-velocity impact tests of TMC composites, and high-velocity impact tests followed by compressive tests.

2.1. Material

SiC fiber/titanium matrix (Ti-3Al-2.5V) composites were fabricated using HIP(Hot Isostatic Pressing) process. In order to improve the damage resistance property, TMC composites covered by titanium (Ti-6Al-4V) clad layers were also fabricated. Thickness of the prepared specimens is summarized in Table 1. The SiC fiber diameter was about 100 μm, and the fiber volume fraction of TMC was about 33%. Cross-sectional image of the prepared TMC plate with clad layers is shown in Figure 1. The basic mechanical properties are referred to Refs. [4,5]. SiC/Ti and Ti exhibit elastoplastic behavior before failure. Plastic properties were evaluated by Hill and Mises yield functions for SiC/Ti and Ti, respectively.

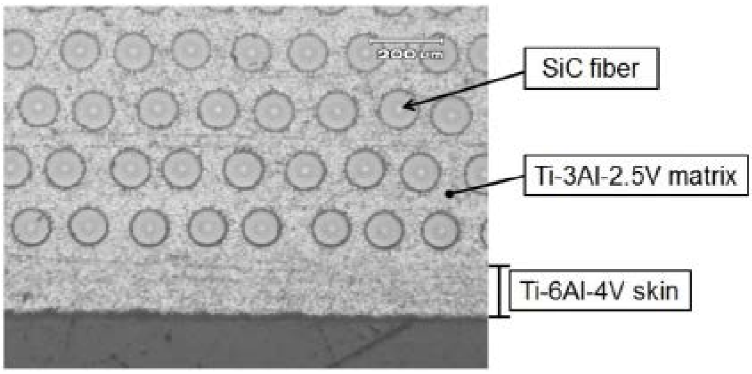

Figure 1. Cross-sectional view of TMC specimen with clad layers.

2.2. Low-velocity impact test

For low-velocity impact tests, drop-weight testing equipment, Instron Dynatup 9250, was used. The impactor is made of steel, and its tip shape is hemispherical with the diameter of 15.9mm. A TMC specimen with 100mm length in the SiC fiber direction and 75 mm width was sandwiched by the fixture with 80mm×60mm rectangular hole, and was clamped by lightly tightening the bolts on the four corners of the fixture. Impact load was applied to the specimens by the fall of the impactor with hemispherical steel tip, whose diameter was 15.9mm, at the center of the specimens. The total mass of the impactor was 15.56 kg. Experimental setup is shown in Figure 2. Three levels of impact loading (impact energy of 20, 45, and 70 Joules) were applied to the TMC specimens (No. 1 and No. 2 specimens in Table 1). After the impact events, ultrasonic inspection was performed to investigate the inner damage behavior of TMC composites. Nonlinear resonant ultrasonic method [6] was applied in this study. Some specimens were also cut to observe the damages by the optical microscope.

Type	No.1	No.2	No.3	No.4	No.5	No.6
Impact test	Low velocity	Low velocity	High velocity	High velocity	High velocity	High velocity
Thickness of SiC/Ti [mm]	3.0	3.0	2.0	2.0	2.0	1.2
Thickness of clad layer [mm]	0	0.4	0	0.2	0.4	0.8
Total thickness [mm]	3.0	3.8	2.0	2.4	2.8	2.8

Table 1. Specification of specimens used for impact tests.

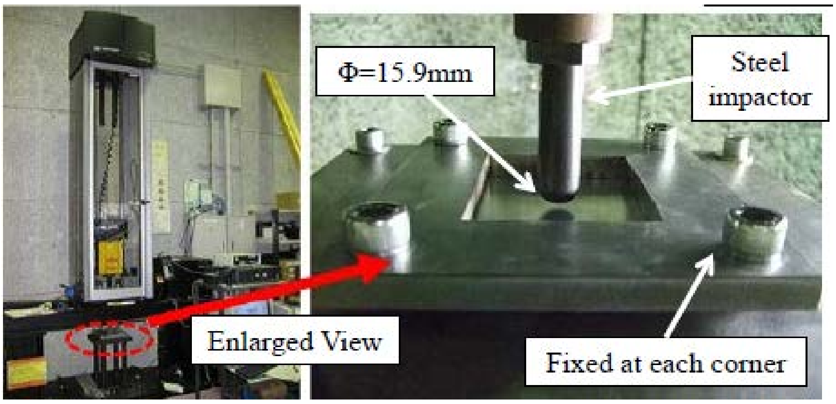

Figure 2. Experimental apparatus of low-velocity impact test.

2.3. High-velocity impact test

For high velocity impact (HVI) tests, gas-gun testing equipment was used as shown in Figure 3. The projectiles are spherical shape with the diameter of 15 mm, made of Al_2O_3, and about 7g in weight to simulate stones on the runway. No. 3 to No. 6 specimens in Table 1 were submitted to high-velocity impact tests, and in-plane specimen size and boundary conditions are the same as low-velocity impact tests. Impact velocity was adjusted to 100, 125, 150m/s (corresponding impact energy: about 40, 55, 80J, respectively). Out-of-plane displacement of the central point was measured from the opposite side of impact loading with a laser displacement sensor. Ultrasonic inspection was also applied to the specimens after impact events.

2.4. Compression-after- impact test

Compressive tests were conducted using the modified small fixtures [7] in reference to compression-after-impact test method of CFRP for intact and high-velocity impacted specimens (No. 3 - No. 6). Six strain gauges were put along fibers on each specimen: four near the top edge, and two near the damaged area. Instron 44R1128 was used as testing equipment with crosshead speed of 0.5mm/min.

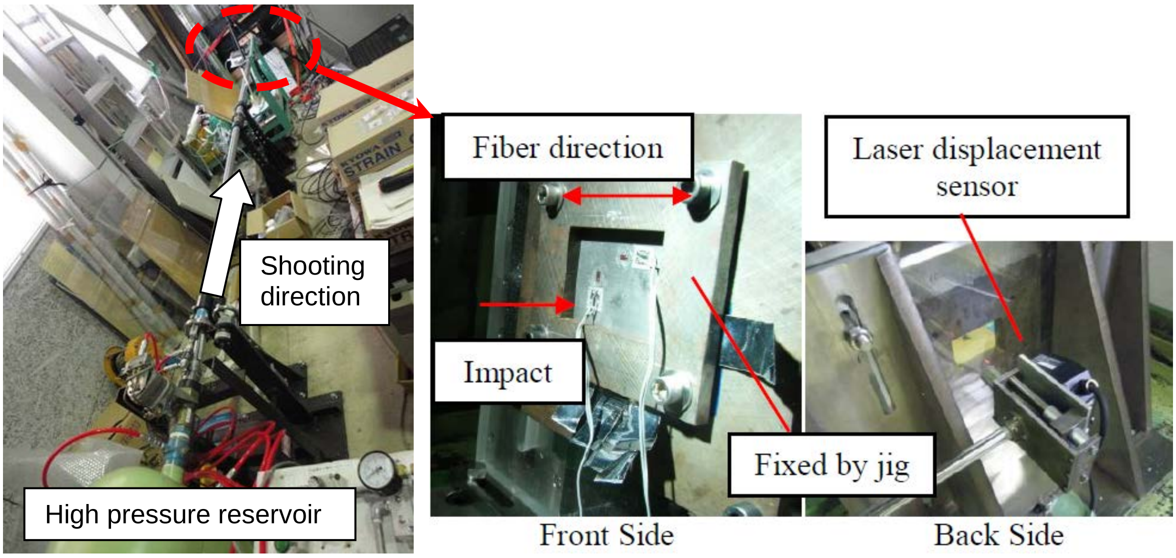

Figure 3. Experimental apparatus of high-velocity impact test.

2.5. Damage characterization of impacted TMC

Apparatus of impacted specimens and microscopic cross-sectional views of the TMC near the impact point suggest that fiber breakage, fiber/matrix debonding, and major transverse crack along fiber direction are the main damage mechanisms in addition to plastic deformation. Clad layers contributed to mitigation of impact damages significantly. Ultrasonic inspection results of the impacted specimens are depicted in Figure 4. The horizontal strip of damage indicates major cracks parallel to fibers and related debondings, while the vertical damage mainly indicates fiber breakage. The elliptically expanded damage detected noticeably in Figure. 4(a) implies debonding between fibers and matrix. Figure 5 shows the relationship between damaged area and impact energy per unit thickness for low-velocity and high-velocity impact tests. High-velocity impact damages are localized at the vicinity of impact points compared to low-velocity impact damages, especially for the cases of specimens with clad layers.

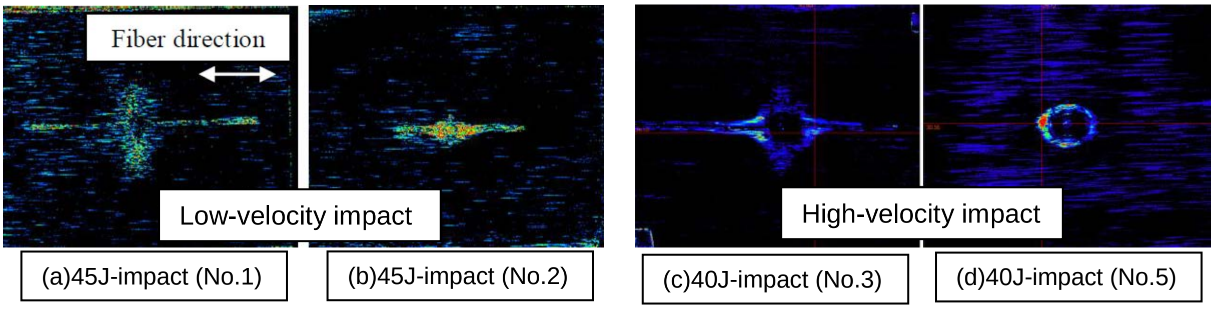

Figure 4. Ultrasonic inspection results of the impacted specimens.

2.6. Compressive strength of impacted TMC

During compressive tests of impacted specimens, out-of-plane deflection became significant at high compressive loads owing to initial deflection at the impact points. Buckling load was estimated by applying the δ^2 method using load versus strain data. The results will be presented in the numerical section (Table 3). Note that the buckling load of No. 6 specimen decreases gradually as impact energy per unit thickness increases compared to other specimens, which indicates the cladding layers' role of moderating impact-induced damage.

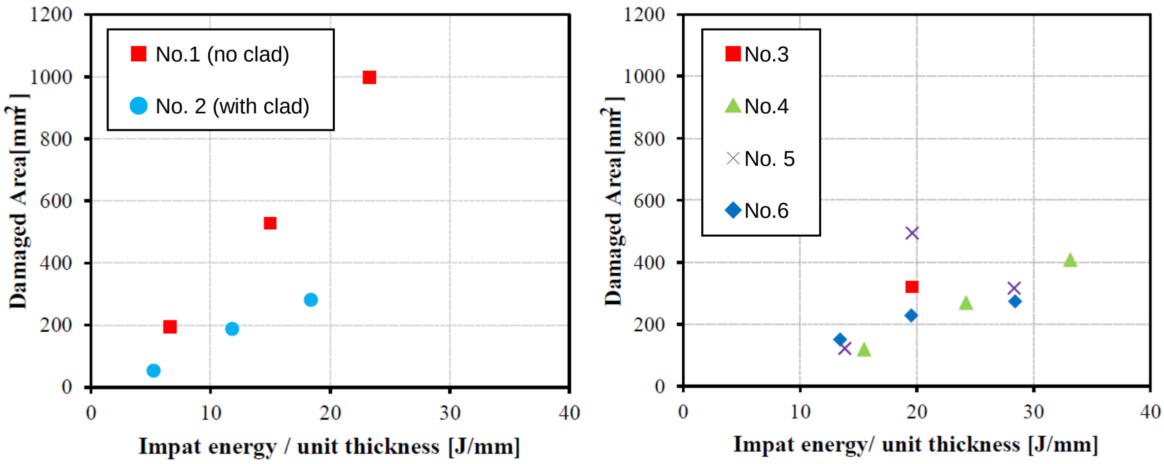

Figure 5. Relationship between damaged area and impact energy per unit thickness (left: low-velocity impact, right: high-velocity impact).

3. Numerical Analysis

3.1. Finite element modeling

When TMCs are subjected to impact loadings, yielding, fiber/matrix debonding, and fiber fracture occur in TMCs. Thus, yielding, strength-based damage onset, and stiffness degradation due to damages of TMC and titanium clad layers are incorporated in the finite element modeling using MSC Marc software as described in our previous study [7]. SiC/TI and clad layers are treated as homogeneous anisotropic (transversely isotropic) materials and isotropic materials, respectively, and they are discretized as 8-noded solid elements.

To simplify such complex interaction between damage and plasticity in SiC/Ti, two modeling methods about the behavior of SiC/Ti were adopted: (i) Final failure of elements is judged by a criterion based on stress, and all stiffness constants reduce to 1 percent of their original values immediately after an element reaches final failure. (ii) Except for final failure, SiC/Ti shows no stiffness degradation, i.e. material nonlinearity of SiC/Ti is caused only by plasticity. Yield functions used were Hill for SiC/Ti and Von Mises for cladding layers (Ti-6Al-4V). In order to incorporate possible failure modes based on the experiments into the models, the failure criterion of SiC/Ti was selected simply as,

$$\sigma_x = X_t, \quad \sigma_y = Y_t \tag{1}$$

where X_t is tensile strength in 0° direction of SiC/Ti, Y_t is tensile strength in 90° direction of SiC/Ti, σ_x and σ_y are stress components of the elements in the fiber direction and transverse direction, respectively. Dynamic simulation using the single-step Houbolt implicit method was adopted, and during calculation, the time steps were properly shortened at the increments when it was difficult to converge the results because of severe damages in specimens.

3.2. Impact damage simulation

Numerical damage simulation on the drop-weight (low-velocity) impact tests of TMC specimens was performed. Considering calculation cost required, the finite element models had a reduced 1/4 part of the experiments for specimens. Out-of-plane displacements of nodes which contact the clamping fixtures were fixed to zero. The impactor was modeled as stiff elements which have same mass, stiffness and tip shape as the experiment.

Simulated impact force history of TMCs subjected to 45 joules impact is presented in Figure 6 in comparison with experimental time history. The figure suggests good agreement between the simulated results and the experimental data. The experimental and numerical results are, however, somewhat different during unloading process. This discrepancy comes from the material model adopted in this study. The present analysis does not consider stiffness degradation due to minute damages before catastrophic failure, resulting in overestimate of the residual stiffness during unloading process. Figure 7 indicates that the present simplified model can estimate the mechanical behavior during loading process even though the unloading behavior is somewhat inaccurate. Therefore, the authors consider that the present simplified model is useful to predict the damage accumulation of TMCs.

The simulated damage area after the impact corresponding to Figure 6 is shown in Figure **7**. In this figure, colored elements indicate the plastically deformed elements in SiC/Ti with equivalent plastic strains over 0.26% (catastrophically damaged elements are included). Because of the simplified method with respect to material modeling, minute damages like fiber/matrix debonding are not able to appear as damaged elements in the calculated results. On the other hand, such minute damages have a close relation to equivalent plastic strain in this model. Comparison with experimental damage behavior determined the threshold of equivalent plastic strain as mentioned above. The numerical simulation agrees well with the experimental damage trend. The numerical model can capture the damage modes including major transverse crack along fiber direction and elliptic damages near the impact point. In addition, the analysis shows the mitigation of impact damage owing to clad layers clearly. The projected damage areas predicted by the simulation are summarized in comparison with the experimental ultrasonic results in Table 2. The predicted damage areas show relatively good agreement with the experimental results, especially for SiC/Ti without clad layers. Although the accuracy of the numerical simulation for SiC/Ti with clad layers is to be improved, the simplified numerical model predicts the damage modes of SiC/Ti composites, damage mitigation by clad layers, and the damage area by impact loading with intermediate accuracy.

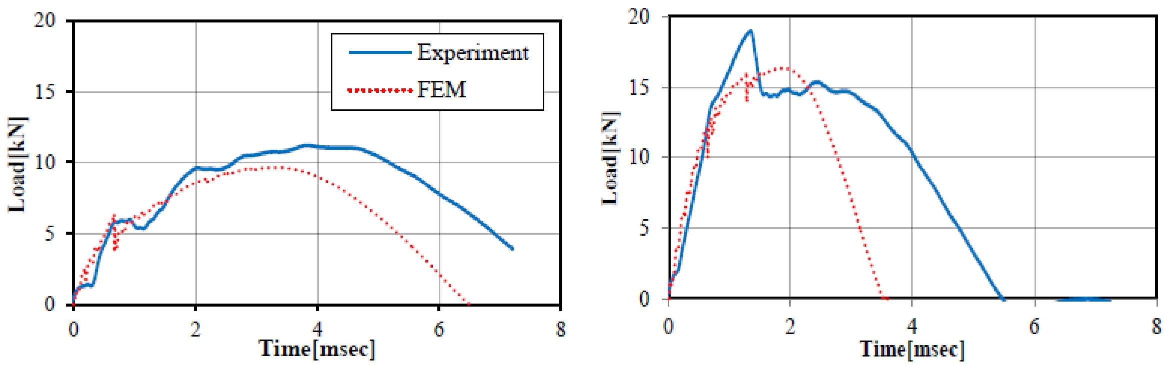

Figure 6. Simulated impact force history subjected to 45 J low-velocity impact (left: SiC/Ti (No.1), right: SiC/Ti with clad layers (No. 2)).

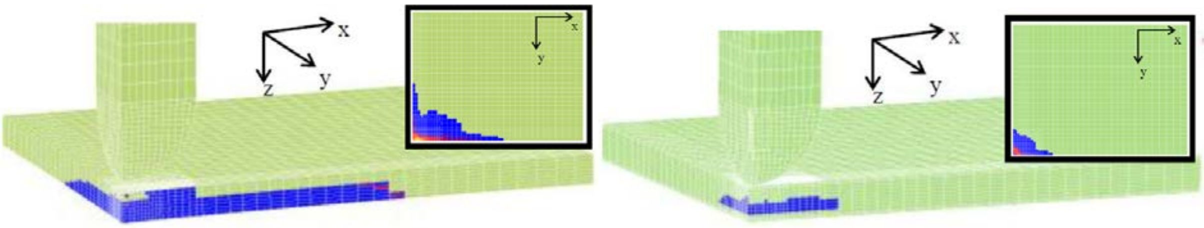

Figure 7. Simulated damage area after 45 J low-velocity impact (left: SiC/Ti (No.1), right: SiC/Ti with clad layers (No. 2)).

The developed numerical model was also applied to high-velocity impact simulation. The central deflection history of TMC specimen (No. 5) during the 100m/s impact and the resulting damage state were simulated as presented in Figure 8. Simulated displacement exhibited similar history to the experiment (at least while loading). Predicted damage area coincided with the experimental result (See Figure 5). Just as the case of low velocity impact, good agreement between experimental and numerical results was confirmed.

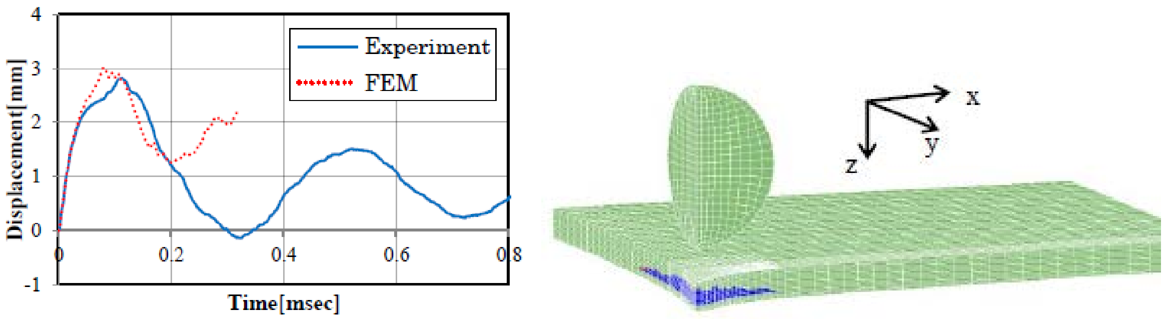

Figure 8. Simulated central displacement history and the accumulated damage area after 100m/s high-velocity impact of SiC/Ti with clad layers (No.5).

Finally, residual compressive strength of TMC specimens after high-velocity impact was simulated. Significant nonlinear behavior was simulated under compressive loading owing to the plastic deformation. The buckling load was calculated using the same way in the experimental evaluation. The predicted buckling load was then normalized by the buckling load of intact TMCs. Comparison of normalized buckling load between the simulation and the experiment is summarized in Table 3. It was confirmed that the residual strength could be accurately simulated using the present model.

Specimen	Impact energy [Joule]	Damage area [mm^2] (simulation)	Damage area [mm^2] (experiment)
No.1 (SiC/Ti)	20	196	192
	45	548	548
	70	1140	997
No.2 (SiC/Ti with clad layers)	20	51	52
	45	132	187
	70	207	279

Table 2. Comparison of projected damage area of TMCs after low-velocity impact between simulation and experiment.

4.Conclusion

Low-velocity and high-velocity impact tests of SiC/Ti composites were conducted to investigate damage mechanism in relation to the application of SiC/Ti composites to aircraft landing gear structures. Observation of damage behavior indicated that possible failure modes of TMCs were major transverse crack, fiber breakage, and debonding. Both impact-loading and compression-after-impact tests suggested that cladding layers mitigate damage accumulation of SiC/Ti inside and compressive strength reduction. The finite element model proposed here showed good agreement on both damaged area and transient behavior during impact while loading for both low-velocity and high-velocity impact cases. It was also confirmed that the predicted residual strength agrees with experimental results. The present modeling is expected to be useful for the actual design of composite landing gear structures with damage tolerant consideration.

Specimen	Impact velocity [m/s]	Normalized buckling load (simulation)	Normalized buckling load (experiment)
No.4	100	0.60	0.63
	125	0.29	0.56
	150	0.16	0.36
No.5	100	0.78	0.73
	125	0.67	0.54
	150	0.52	0.42
No.6	100	0.93	0.88
	125	0.83	0.75
	150	0.75	0.58

Table 3. Comparison of normalized buckling load of TMCs after high-velocity impact between simulation and experiment.

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