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FOD CHARACTERISTICS OF TITANIUM METAL MATRIX COMPOSITE (TMC) TO APPLY AIRCRAFT LANDING GEAR STRUCTURE

Norio TAKAHASHI*, Toyohiro SATO*, Kouta Fujiwara*,
Tomohiro Yokozeki, Akinori Yoshimura*** and Hirokazu Shouji*****
*** Sumitomo Precision Products Co., Ltd.**
****The University of Tokyo, Graduate School of Engineering,**
*****Japan Aerospace Exploration Agency (JAXA)**

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Abstract

We have developed a prototype Titanium Metal Matrix Composite (TMC) Landing Gear Components as a potential replacement for Ultra-High Strength Steel (300M) Components and have achieved a 30% reduction in weight, and mitigated the risk of corrosion and in-service problems associated with 300M.

In this paper, we describe the Foreign Object Damage (FOD) characteristics of TMC as the composite material in the both view point of experimental and analytical approach. Considering these results, we made the design study of the TMC Landing Gear components to apply the Side Stay and the production cost was also estimated. The conclusions show that the structural integrity of the TMC Landing Gear Components is superior as the future innovative marital of the Landing Gear but the production cost is still too high to introduce the next generation Commercial Aircraft Landing Gear components.

1 General Introduction

Through our Landing Gear design and development experiences, we have used Ultra-high Strength Steel 300M[1]. However, if the 300M component is not designed, manufactured, and processed properly, corrosion and/or fatigue problem may occur in-service. Recently, as another solution, CFRP drag and side braces for the Main Landing Gear of the Boeing 787-8 were developed by Safran/Messier-Bugatti-Dowty as the world first application to the Landing Gear as shown in Fig. 1. In addition, UTC Aerospace Systems is developing CFRP Upper and Lower drag braces for F-35 Lightning II Main Landing Gear in collaboration with Fokker Landing Gear.

Fig. 1 787 MLG CFRP Drag and Side Stay

As another solution for the future Composite Landing Gear material, we are proposing and developing Titanium Metal Matrix Composite (TMC). We can achieve a 30% weight reduction of the component, and mitigate the risk of corrosion problems associated with 300M material.

As described in SAE Document AIR55522[2], we have to study the behavior of Composite Landing Gear components when the part is subject to Foreign Object Damage(FOD), and reflect such behavior when considering the component design. In this paper, we describe the results of Foreign Object Damage (FOD) to the TMC through high and low speed impacts tests. In addition, we analyzed the FOD behavior to the TMC material. Considering the good coincidence of the experimental and analytical results, we reflected the design consideration to the single-aisle commercial aircraft Landing Gear components and estimated the production cost of the components to confirm if the cost is acceptable level.

2 Material Properties of TMC

The typical material properties are shown in Table 1. Comparison of the specific strength and stiffness with typical aerospace structural materials is shown in Fig. 2. As show in this figure, TMC has a higher specific strength and stiffness than 300M.

Table 1 Material Properties of TMC

Material Properties	Specific Value
Fiber	Silicon Carbide
Tension stregnth of Fiber	3200 MPa
Stiffness of Fiber	330 GPa
Tension strength of Matrix(Ti6-4)	935 MPa
Stiffness of Matrix(Ti6-4)	105 Gpa

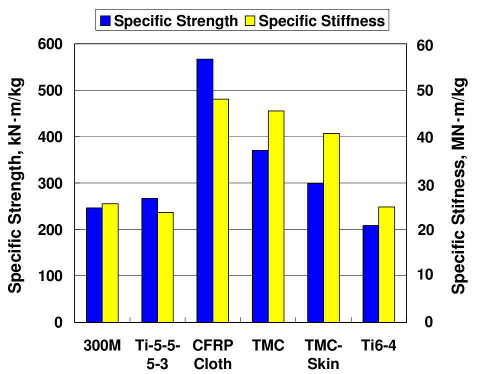


Fig. 2 Specific Strength and Stiffness of Materials

3 Low Speed Impact Test Summaries

Since the detail of test setup and the test results were already reported in Reference [3], we summarize the low speed impact test results in this paragraph. Low speed impact test was conducted to the Test Panels show in Table 2, and the typical results at 45 joules are shown in Fig. 3, together with the Non-destructive test (NDT) inspection results observed by the Nonlinear Resonant Ultrasonic Testing (NLRUT) method.

Table 2 Specification of Test Panel

TP Name	Ti Clad layer (mm)	TMC Layer (mm)	Total thickness (mm)
TMC	0.0	3.0	3.0
TMC+Ti04	0.4	3.0	3.8

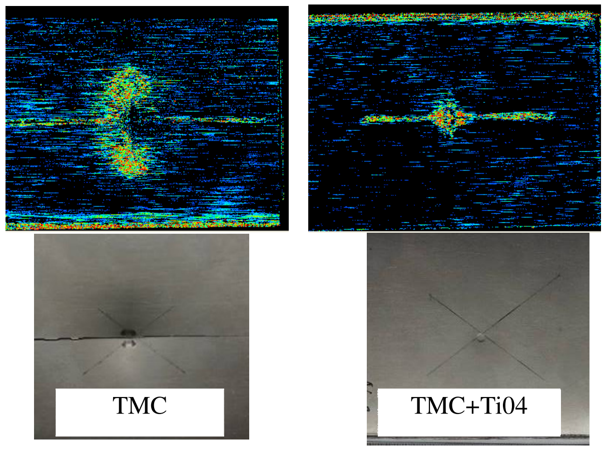


Fig. 3 Low Speed Impact Test Results at 45 joules

The following results were obtained from low speed impact test;

(1)For the “TMC” Panel, a surface crack occurred after the 45 joule impact, but for the “TMC+Ti04” Test Panel, no surface crack occurred and the damage was alleviated.
(2)NDT inspection results indicate the correct damage area in the TMC.

Test Panels were cut off to visually check the damage, and we found that the damage was typically delamination and fiber failure as shown in Fig. 4.

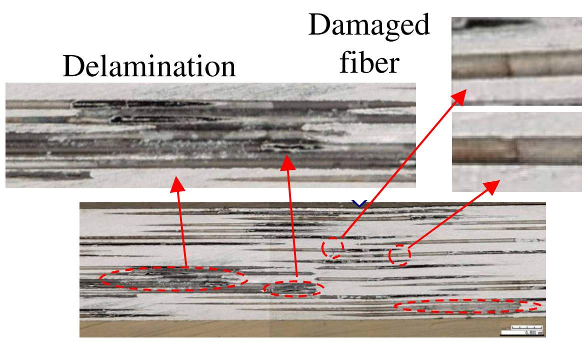


Fig. 4 Cross section of Test Panel after Impact

4 High Speed Impact Test

4.1 Test Setup

We further studied the damage effect of TMC by high speed impact due to debris impact like small stones during aircraft operation. Test Panel of 100×75mm size was used. Specification of the Test Panel is shown in Table 3. Four types of Test Panels were evaluated, that is, one is unclad composite and others are clad by three different thickness of Ti.

Table 3 Specification of Test Panel

TP Name	Ti Clad layer (mm)	TMC Layer (mm)	Total thickness (mm)
TMC	0.0	2.0	2.0
TMC+Ti02	0.2	2.0	2.4
TMC+Ti04	0.4	2.0	2.8
TMC+Ti08	0.8	1.2	2.8
CFRP(REF)	0	0	2.2

We used the JAXA's small-scale gun tube apparatus, as shown in Fig. 5, and 15mm diameter aluminum ball as the flying object. We adjusted the ejection speed of the flying object to 360km/hr (100m/sec), 50km/hr (125m/sec) and 540km/hr (150m/sec), which were equivalent to 40, 55 and 80 Joules, respectively. When testing, we recorded the displacement and dynamic behavior data by the high speed camera, laser displacement and strain gauges as shown in Fig. 6.

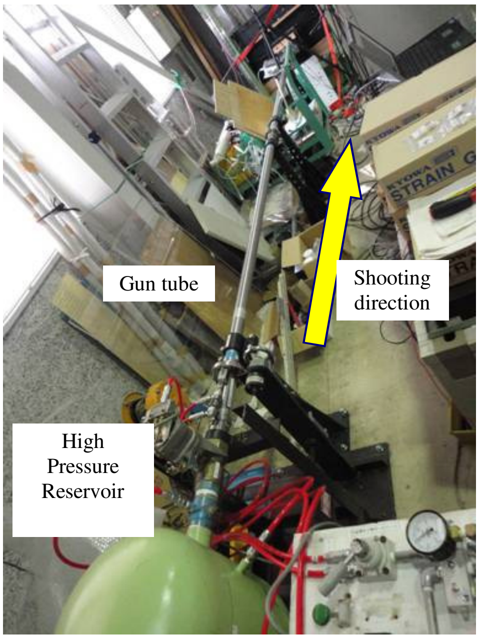


Fig. 5 JAXA's Small-scale Gun Tube Apparatus

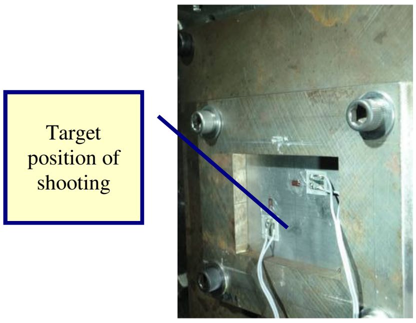


Fig. 6 Test Panel Set Up on the Apparatus

4.2 Test Results

Typical test results are shown in Fig. 7 .The following results were observed;

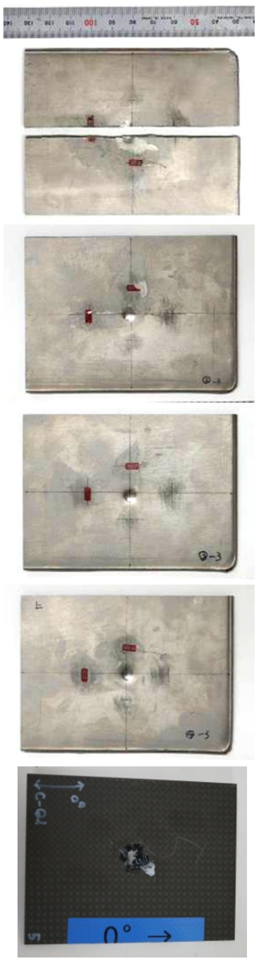
(1)For the test panel of "TMC", the test panel was completely split by the impact of 40 Joules.
(2)Ti6-4 surface clad improved the anti-FOD characteristics of TMC. For the test panel of "TMC+Ti02", no split was observed and the surface crack was reduced to 65 mm against the 80 Joules Impact Energy.
(3)For the test panel of "TMC+Ti04", no surface crack was observed against the 55Joules Impact Energy.

Although unclad TMC has a poor anti-FOD characteristics, the Ti6-4 surface clad improves the anti-FOD characteristics and we found that the metal clad on the TMC surface will be required if the FOD characteristics should be improved for TMC components.

Comparing the low speed impact test results described in Paragraph 3 and CFRP(REF) test results, we can conclude the followings;

(1) High speed impact causes smaller damage to TMC than low speed impact.
(2) The impact time is 1.5 msec for high speed and 3msec for low speed. This means that the high speed impact localized the impact area on the TMC.
(3) The Ti6-4 surface clad improves the impact effect, and as increasing in its thickness, the anti-FOD characteristics approached asymptotically to the metal's one.
(4) For the impact energy of 40 Joules, the flying object penetrated the CFRP test panel.

However, no crack or separation as unclad TMC was observed because the CFRP test panel was composed of 0/90deg cross ply cloth.



(a) TMC 40J
Crack: split

(b) TMC+Ti02 55J
Dent thickenss:1.4mm
Surface crack: 65mm

(c) TMC+Ti04 55J
Dent thickness: 1.3mm
Surface crack: None

(d) TMC+Ti08 55J
Dent thickness: 1.0mm
Surface crack: None

(e) CFRP(REF) 40J
Penetarated

Fig. 7 High Speed Impact Test Results

4.3 CAI test after High Speed Impact Test

We conducted the Compression After Impact (CAI) Test of the Test Panels receiving the high speed impact above. Test set up is shown in Fig. 8. We measured the strains on the Test Panel both surfaces.

Fig. 8 shows the Test Panel setup after CAI test. Since the Test Panel was permanently deformed due to the impact load, it was difficult to apply the compression load to the Test Panel without the effect of the bending moment. The typical Stress-Strain data is shown in Fig. 9. During the CAI test, we confirmed the continual acoustic emission from about 60% maximum compression load, and finally buckling occurred together with the large breaking sound at the maximum load. Test Panels have plastic deformation due to the buckling.

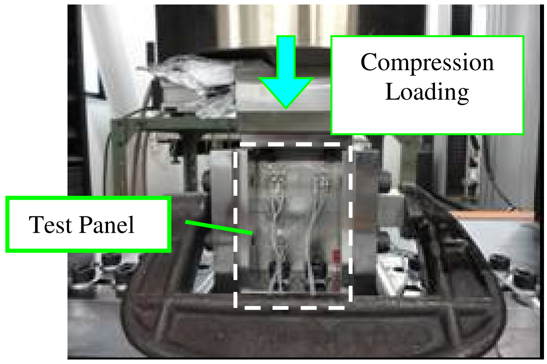


Fig. 8 CAI Test Set-up

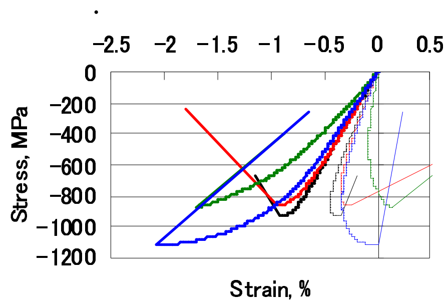


Fig. 9 Typical Stress-Strain Curve

We summarize the residual Buckling Strength and residual Stiffness in Fig. 10 and Fig. 11, respectively.

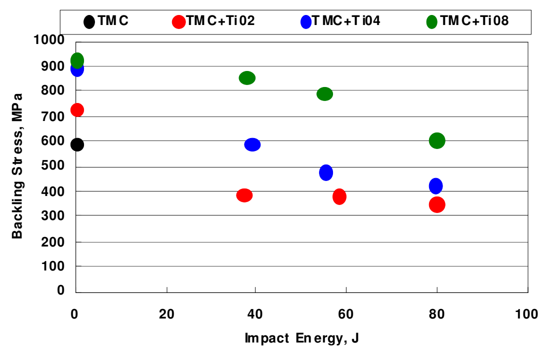


Fig. 10 Residual Bucking Stress from CAI Test

We found the followings from the CAI test of TMC Test panels;

(1) The residual buckling strength and the residual compression stiffness degraded with increased impact energy.

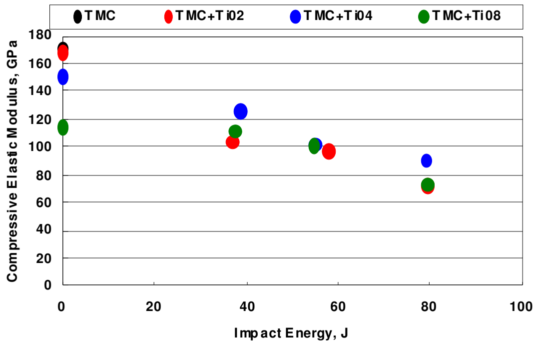


Fig. 11 Residual Compression Stiffness from CAI Test

(2) For the test case of "TMC+Ti02" and "TMC+Ti04", the 40 joules impact largely decreased the buckling strength. We think that the threshold level of the fiber damage is between 20 to 40 joules for these Test Panels.

(3) For the test case of "TMC+Ti08", we think that the threshold level of the fiber damage is between 40 to 80 joules.

(4) There are similar results for the residual stiffness to the residual buckling load.

(5) The residual buckling load and the residual compression stiffness seem to degrade to some asymptotic value, that is, 40 to 60 % of original value, against the impact energy.

(6) The Ti6-4 clad improves the anti-FOD characteristics with its increase of thickness. This is the same conclusion with the low speed impact test results.

5 Analytical Approach of TMC Impact Test

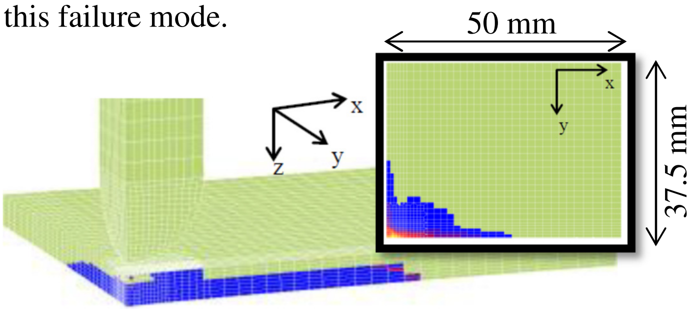
We conducted the FEM analysis to simulate the impact test of the TMC Test Panels[4][5]. The Test Panel end was restricted to simulate the test in our analysis. In addition, to simplify the interaction and delamination between SiC fibre and Ti matrix, the following damage criteria were applied;

(1) When the stress of the element rises over the ultimate tensile stress (F_{tu}) of SiC/Ti or Ti clad, the damage occurs and then its stiffness is reduced to less than 1% of the original.

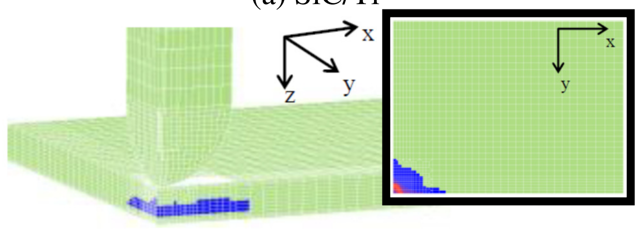
(2) The material breaking is not considered in the analysis and the material non-linearity is only due to the plastic deformation.

(3) The crack of the Ti clad is simulated by separating the nodes between subject elements if the tensile stress rises over F_{tu}.

The analytical results for low speed impact test at 45J with and without the Ti clad are shown in Fig.12 respectively. The results show that the cracks parallel and vertical to the fibre direction were observed. In our analysis, the delamination between SiC and Ti matrix cannot be observed because of non-consideration of this failure mode.



(a) SiC/Ti



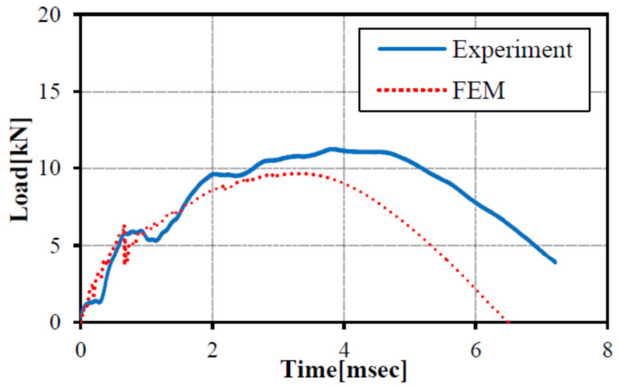
(b) SiC/Ti with Ti clad

Fig.12 Damage area (matrix crack and fibre damage)

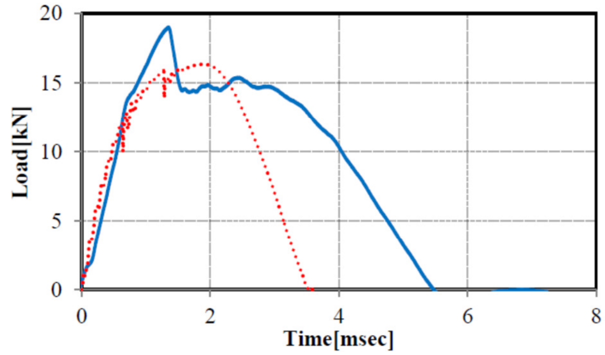
Table 4 shows the comparison of the damage area between the experiments and our analysis against the low speed impact energies. In addition, Fig. 13 shows the time chart of the impact load after impact observed in the experiments and obtained by our analysis. These results show the good correlation between experiments and our analysis although we found some discrepancy in the impact load alleviation phase. We think that this discrepancy is caused by the simplified stiffness criteria for the damaged FEM element.

Table 4 Comparison of damage area between experiments and analysis

Type	Without clad			With clad		
Energy(J)	25	40	70	25	40	70
Experiments (mm^2)	192	548	997	52	187	279
Analysis (mm^2)	196	547	1140	51	132	207



(a) SiC/Ti



(b) SiC/Ti with Ti clad

Fig.13 Impact load time chart

The analytical results for high speed impact test at 100m/s 40J with Ti clad are shown in Fig.14 together with the displacement time chart of the back side of the impact point. The analysis shows that the damage area for the high speed impact test is smaller than for the low speed impact test and the displacement time chart has a similar tendency as the low speed impact case.

From the above discussion, our analytical approach is coincident with the experiments in the point of the damage area prediction and the dynamic behavior induced by the high speed or low speed impact. We can conclude that our analytical model can predict the residual strength after impact as the preliminary study tool of the TMC structure although the model should be still improved to predict this behavior more correctly. As the next step, we apply this analysis to the design study of TMC Side Stay.

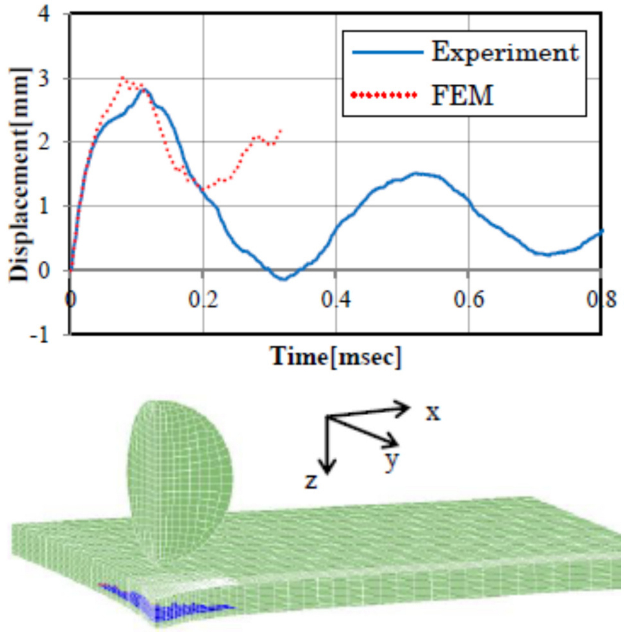


Fig.14 Damage area and Displacement time chart for the high speed impact

Firstly we studied the crack propagation rate of the TMC pipe assuming that the 10 mm or 100 mm crack along the fibre direction initially occurs due to some impact as shown in Fig.15. To simplify this study, we do not consider the plastic deformation of the TMC pipe due to the impact. The crack propagation analysis shows that no crack propagation occurred in both the case of 10mm and 100 mm crack length cases.

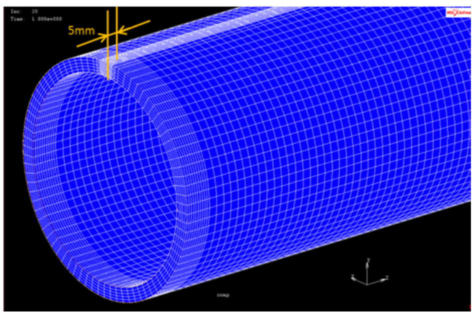
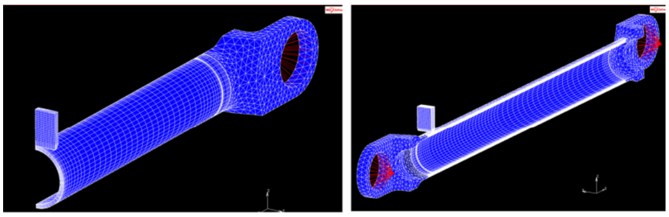


Fig. 15 Crack Propagation Analysis

Secondly we applied this analytical method to predict the residual strength of the TMC Side Stay after impact. In our analysis, the Side Stay model and the impact energy described in Paragraph 6 was used. We consider the two impact points that one is the center position and the other is the joint area between the TMC pipe and the Ti Clevis end, and calculate the residual compression stress of the TMC Side Stay after high speed impact as shown in Fig.16.



Impact Point: Center Position   Impact Point: Joint Area

Fig.16 Impact model of TMC Side Stay

The impact damage analyses of the TMC Side Stay against the center position and joint area are shown in Fig. 17 and Fig. 18, respectively. We conducted the compression residual strength analysis after impact, and typical results for the case of without Ti clad and with 0.5mm Ti clad are shown in Fig.19.

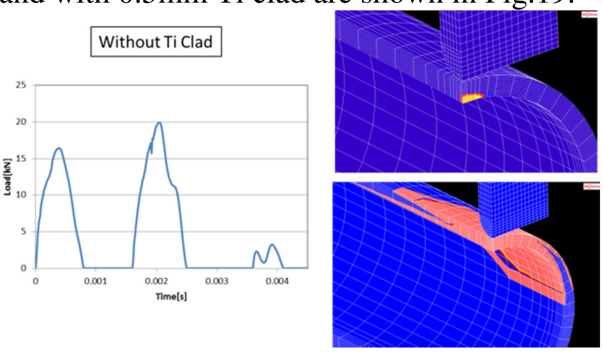


Fig. 17 Impact Analysis at the Center Position

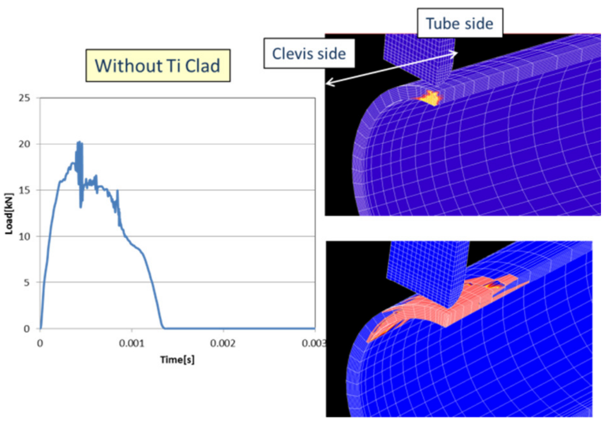
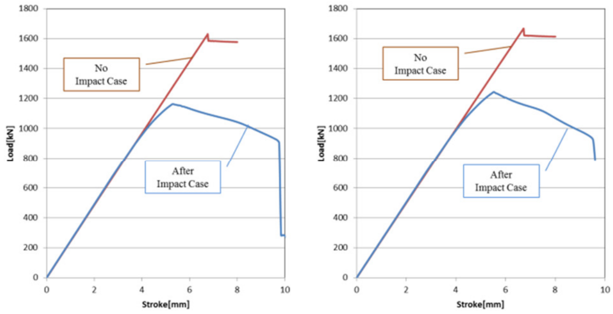


Fig. 18 Impact Analysis at the Joint area



(a)without Ti Clad (b)with 0.5 mm Ti Clad

Fig.19 Compression Test of TMC Side Stay

To verify our analysis, we applied this analysis to the TMC side stay low speed drop test, as shown in Fig.20, described in the Reference [3].

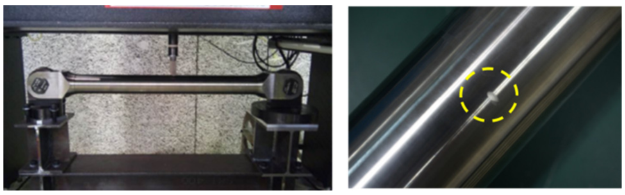


Fig.20 40J Low Speed Impact Test to TMC Side Stay

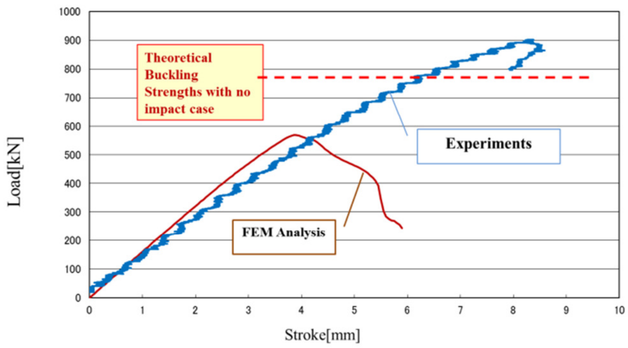


Fig.21 Comparison of CAI Test between Experiments and Analysis

As shown in Fig.21, we confirmed that our analysis estimated the residual compression strength after impact conservatively, so we can apply our preliminary design study of the TMC side stay described in next Paragraph.

6 Design study of the TMC Side Stay

Considering the TMC material properties and its FOD characteristics described in the Paragraph 2 to 5, we designed the Side Stay component for the single aisle aircraft as the following design load conditions;

(1) Limit Load: 360 kN for Tension
(2) Limit Load: 680 kN for Compression
(3) Ultimate Load: 540 kN for Tension
(4) Ultimate Load: 1020 kN for Compression
(5) Fatigue Tension Load: 111 kN x 800 Kcycles
(6) Fatigue Compression: Load 408 kN x 800 Kcycles

The TMC Side Stay consists of the TMC tube and the monolithic titanium clevis ends, both ends of which were bonded by the diffusion bonding technology or friction welding technology, as shown in Fig.22. We were able to apply conventional design to the clevis ends and apply the law of mixture between the monolithic titanium and Silicon Carbide fibre for sizing the TMC tube section.

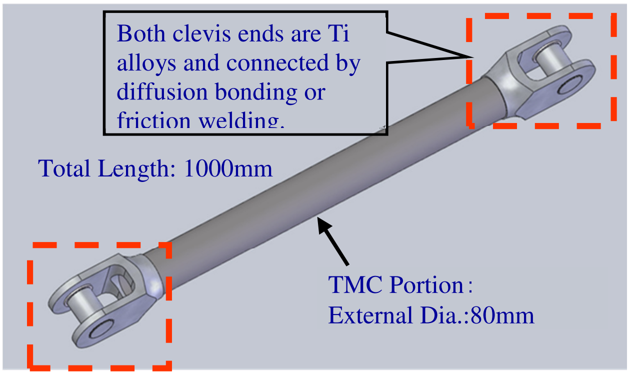


Fig. 22 TMC Side Stay Structure

In accordance with the design guideline document AIR5552[2], we defined the design criteria as our target in Table 5.

Table 5 TMC Design Criteria

	Assessment	Impact energy	Fatigue Strength	Static strength
1	No damage	0	Full life 800K cycles	Ultimate load
2	Defect during the production/ maintenance	6.7J/mm	Full life 800K cycles	Limit load
3	Impact damage during operation 1	50J Stone impact	35K cycles	Ultimate load
4	Impact damage during operation 2	Tire debris	N/A	Limit load

We designed the Side Stay for the three difference material conditions, 300M, Ti-10-2-3, and TMC and we obtained the weight and size as shown in Table 6.

Table 6 Weight and Sizing against the materials

Material	Weight (kg)	OD (mm)	ID (mm)	Wall thickness
300M	13.2 (baseline)	85	76.5	4.25
Ti-10-2-3	11.8 (-11%)	85	69.6	7.7
TMC	9.0 (-32%)	85	74.6	5.2

Assuming the small stone impact of 50J to the TMC tube section and thejoint area of TMC and monolithic Ti was received during the take-off and landing, we conducted the impact effect and post impact crack initiation analysis and the residual compression strength as shown in Table 7. The following results were obtained;

(1) No crack initiation is obtained after impact;
(2) The residual compression strength is depending on the Ti clad thickness but all cases guarantee the Ultimate Compression load.
(3) No Ti clad layer requested to the protection of the impact damage. This means that the maximum weight reduction can be achieved.

Table 7 Residual Compression Strength

Case	Ti-clad (mm)	TMC layer (mm)	Residual compression strength(kN)
A	0.0	5.2	1,120
B	0.2	4.96	1,160
C	0.3	4.84	1,172
D	0.5	4.73	1,241

7 Cost Study of TMC Side Stay

In order to introduce the TMC material to the Commercial Aircraft Landing Gear components, we conducted the feasibility study of the target cost and found the following output from the market needs;

(1) Weight reduction; -30% from 300M material
(2) Production Cost; less than Ti-10-2-3

As described in the Paragraph 6, we can verify that the 30% weight reduction is achievable. In this section, we describe the estimated production cost based on the single aisle aircraft Landing Gear production rates. For our cost estimation, we assume that the jointing between TMC pipe and the clevis ends is by the friction welding to reduce the production cost. Table 8 shows the estimated costs based on the large production rate.

Table 8 Estimated Production Costs

Material	Weight (kg)	Cost	Comment
300M	13.2	25	Baseline
Ti-10-2-3	11.8	100	
TMC	9.0	150	

We show the production cost analysis of the TMC best case scenario in Fig. 23.

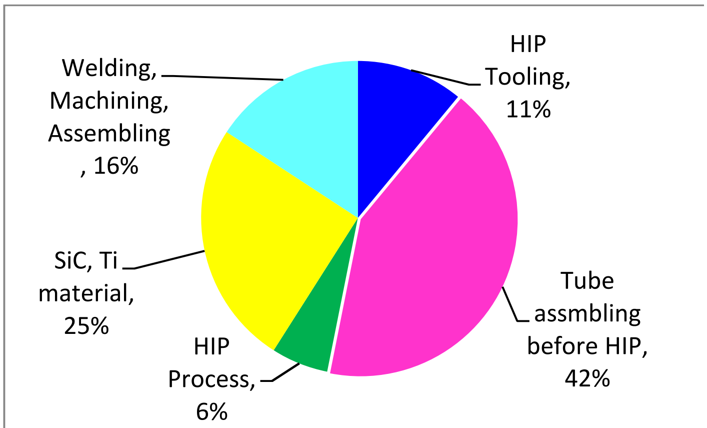


Fig. 23 Production Cost Analysis of TMC components

In Fig.23, we find that for the best scenario case the 84% raw material cost composed of SiC material(25%), HIP tooling (11%),Tube assembling(42%), and HIP process(6%) is too high. In order to achieve the production cost level less than Ti-10-2-3, we have to reduce the 24% total cost, which is equivalent to the 30% raw material cost reduction. To achieve this, we need the following step change of the production cost reduction;

(1) Introduction of large volume production of SiC fibre,
(2) Introduction of automated layup and assembling machine,
(3) Introduction of simplified HIP tooling.

However, we have no confidence to achieve the 30% raw material cost reduction at this phase.

8 Conclusions

In our design study of the TMC application to the Landing Gear Components based on the FOD characteristics, the following conclusions were obtained;

(1) The structural integrity of the TMC Landing Gear Components is superior as the future innovative marital of the Landing Gear in view point of the lighter weight and high strength and stiffness instead of the current 300M low carbon steels.
(2) The FOD analysis predicts the experimental results of both the high and low speed impact test, and can be useful tool of the TMC components design.
(3) However the production cost is too high to introduce the next generation Commercial Aircraft Landing Gear components. To solve this, we still introduce the innovative production process to reduce minimum 50% production costs.

We conclude that TMC will be a potentially future Landing Gear Structural Material if we can solve the fibre cost and process cost reduction.

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8 Contact Author Email Address

mailto: taka-no@spp.co.jp
or fujiwa-k@spp.co.jp

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