HIGH MODULUS CARBON FIBER/TITANIUM LAMINATES

By

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ABSTRACT

Titanium has been used to meet ever-stricter standards for high-temperature performance, creep resistance, low weight and high strength. Having low density, a high melting point, and high tensile strength, it seems like the perfect material for numerous applications. For structural applications where flexural stiffness and strength play the most important role, titanium's high cost can be a restrictive factor. The cost-effectiveness of the material can be increased by using it together with other less expensive high strength and low weight materials in the form of composite laminates. In this investigation, laminates were fabricated using inorganic matrix/high modulus carbon fiber composites with titanium sheets. Laminates were tested in three-point bending to assess the performance of the upgrade. The results show that combining Geopolymer high modulus carbon composites with titanium sheets significantly increases the performance. Laminates provide a lower cost solution for given stiffness and weight requirements compared with other common structural materials, such as steel and aluminum.

Thesis Supervisor: Jerome J. Connor

Title: Professor of Civil and Environmental Engineering

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1. INTRODUCTION

Since the early 1940's, titanium has been used in new alloys and production techniques to meet ever-stricter standards for high-temperature performance, creep resistance, low weight and high strength. Titanium and its alloys have proven to be technically superior materials for a wide variety of aerospace, industrial, marine and commercial applications. Having low density, a high melting point (1668° C), and high tensile strength it seems like the perfect material for numerous application. Titanium is currently used for applications such as airplane structures, space vehicles, chemical processing equipment, marine components, aircraft engine blades, and rocket motor cases

The main disadvantage of titanium is its very high cost (approximately 25 US dollars per kg). For structural applications where flexural stiffness and strength play the most important role, the high cost can be a restrictive factor. In order to achieve the desired flexural stiffness and strength the cross section of the structural element needs to increase and this leads to an increased weight. The cost-effectiveness of the material could increase by using it with other less expensive high strength and low weight materials in the form of composite laminates. The concept of laminate structures is definitely not new. Historically the first form of combining materials as composites is the laminated wood which was used as far as 3500 years ago (1). Findings of ancient laminated wood structures support the idea that the main principles of a composite system, currently the subject of major research, were physically and empirically understood thousands of years ago.

Polymer composites seem to be the best-suited material to be used with titanium in the form of laminates. Several researchers have investigated laminates made with titanium skins and organic polymer composite cores. Previous research has shown that it is a feasible solution but some issues need to be addressed before becoming commercially available (2-5). One of these problems is the bond between the titanium plates and the composite laminates (2, 4). Another disadvantage is that the polymer matrices used in the composites are organic and they are susceptible to fire. Even in cases where the skins of the system are titanium plates the organic matrix can liquefy at elevated temperatures leading to a structural failure. Since the matrix plays such an important role it is necessary to use a fireproof matrix for structural elements that are required to exhibit high strength, low weight and high temperature.

The presented investigation focuses on the use of inorganic matrix composites as skins with titanium core. The skins were made using made Geopolymers and high modulus carbon fibers. The target was to decrease the cost while keeping the stiffness at the desired levels without making a big compromise on the increase of the weight. This investigation was to evaluate the feasibility of fabricating laminates made of titanium sheets and composites made of high modulus carbon fibers and inorganic matrices. The titanium has typical metallic properties (ductility) and very low density compared to steel. It also exhibits high temperature resistance. These properties will be combined with the properties of ultra high elastic modulus carbon ($E >$ 600 GPa) to obtain a composite that has high specific strength, high modulus and high temperature resistance. In this paper, the initial results from specimens tested in three point bending tests are presented. The experimental work was done in the University of Massachusetts Dartmouth, and was supervised by Chris G. Papakonstantinou.

2. RESEARCH PROGRAM

Commercially available pure grade titanium sheets were used with high modulus carbon fiber tows for the fabrication of composite plates. The titanium core had a cross section of 1.6 mm by 25.4 mm and a length of 205 mm. The sandwich composite laminate was made by bonding high modulus carbon sheets as skins on to the previously described titanium sheets. The high modulus carbon fibers used, were used in the form of tows. A recently developed inorganic resin (Geopolymer) was used for the fabrication of the high modulus carbon fiber laminates. Geopolymer resins have been successfully used for many structural applications. The fabrication of the composite specimens was made utilizing a technique called "hot press vacuum bagging". This technique has been extensively used in aerospace engineering for manufacturing composites. The evaluation of the specimen strength was performed through the testing of specimens in three point bending.

The properties that were investigated include:

- Compatibility of matrix with Titanium.
- Feasibility of making the laminates.
- Failure mechanisms in bending.

2.1 Specimen Details

2.1.1 Resin and Core Preparation

The Geopolymer consists of parts A and B, where Part A is an amber-colored potassium silicate solution and Part B is a white, amorphous, silica powder. The ratio of Parts A and B that was used in the mix was 1:1.35 by mass, respectively. This mix has a molar silica / alumina ratio of 18 and has been proven to increase the water stability in Geopolymer composites (6). The use of Geopolymer as a matrix for fabrication of different composites has been studied extensively (6-9).

A small high-shear mixer containing serrated stainless steel blades is used to mix the components of the resin for a total of 60 seconds. After the first 30 seconds of mixing, any clumps of powder not blended are scraped from the sides of the mixer. Subsequently, the resin is mixed again for another 30 seconds to make sure all components are mixed thoroughly. The pot-life of Geopolymer is approximately 2 hours. It should be noted that the Geopolymer is non-toxic and does not emit any toxins or fumes during the lay-up process.

The titanium surface was initially sanded using a coarse (#40) sandpaper. The titanium sheets were finally washed with a degreaser solution to remove any oil/grease residue from the surface.

2.1.2 Vacuum Bagging Setup and Hand Impregnation

The vacuum bagging setup used for the laminate sample is shown in Figure 1. A 3.00 mm x 280 mm x 600 mm stainless steel sheet was used as the base tool. The sealant tape was stuck on the four edges of the base tool. A nylon vacuum bagging film was the first layer that was placed on top of the steel sheet and inside the sealant tape. On top of the nylon film, a non-porous Teflon peel ply was placed (Figure 2a). The next step includes the preparation of the wet laminate sample by using the standard hand impregnation technique. A small amount of resin was poured on the face of the titanium bar, then, three carbon fiber tows were laid on it. The carbon fiber tows used in the specimens are manufactured by Mitsubishi Chemical. Their properties are listed in Table 1. Another small amount of resin was poured onto the fiber tows and a plastic squeegee was then used to spread the resin evenly over the surface. A plastic grooved roller was used to impregnate the fibers with resin and remove any excess amount of resin. In order to remove any water from the matrix the specimen was placed on a small oven for 3 minutes at a temperature of 100^0F. The titanium bar was then placed on the non-porous Teflon peel ply. Another layer of the Teflon peel ply was placed on top of the specimen. The last layer, a white polyester breather cloth, was placed on top of the Teflon peel ply and was surrounded by the sealant tape (Figure 2b). Consequently, a thru-bag vacuum connector was placed on top of the breather cloth. Finally, a piece of the nylon vacuum bagging film was firmly secured to the sealant tape and the vacuum hose was attached to the thru-bag connector. All materials used are resistant up to temperatures of at least 177^0C (350^0F) to prevent any melting during the heated curing. This procedure was repeated for the other face of the titanium bar the following day.

Table 1: Fiber Properties

Fiber Name	Tensile Modulus (msi)	Tensile Strength (ksi)	Elongation (%)	Density (g/cc)	Filament Count	Filament Diameter (*u*m)	ILSS (ksi)
K63712	93	390	0.4	2.12	12,000	11	11

Figure 1: Vacuum Bagging Setup

2.1.3 Curing Method

Heated curing was the method used to cure the Geopolymer composite. First, the entire vacuum bagging setup is placed into a heated press at a temperature of about 26.7^{0}C (80^{0}F). Figure 3 shows the specimens during the curing phase. An initial pressure of approximately 1.275 MPa (184.82 psi) is then applied to the laminate plate, and the temperature is ramped up to 150^{0}C (302oF) at a rate of 1^{0}F per minute (60^{0}F/hour) to avoid thermal shock to the laminate. Therefore, it takes about 3.5 to 4 hours to reach the desired temperature. Once the temperature of the heated platens reaches 93.3^{0}C (200^{0}F), the full pressure of 2.55 MPa (369.64 psi) is applied. When the temperature of the platens reaches 150^{0}C (302^{0}F), the laminate plate remains at a pressure of 2.55 MPa (369.64 psi) for 3 hours. After the 3 hours period, the heated platens are turned off allowing the ambient temperature to cool slowly the laminate plate. During the curing period, both the pressure and the vacuum are not released. The heated press automatically shuts off itself until the temperature of the heated platens reach 26.7^{0}C (80^{0}F), and the vacuum is finally turned off. A total of 24 hours is needed for the curing process. Finally, the laminate plate is removed from the bagging system and allowed to cure an additional 30 days at room temperature in the laboratory environment.

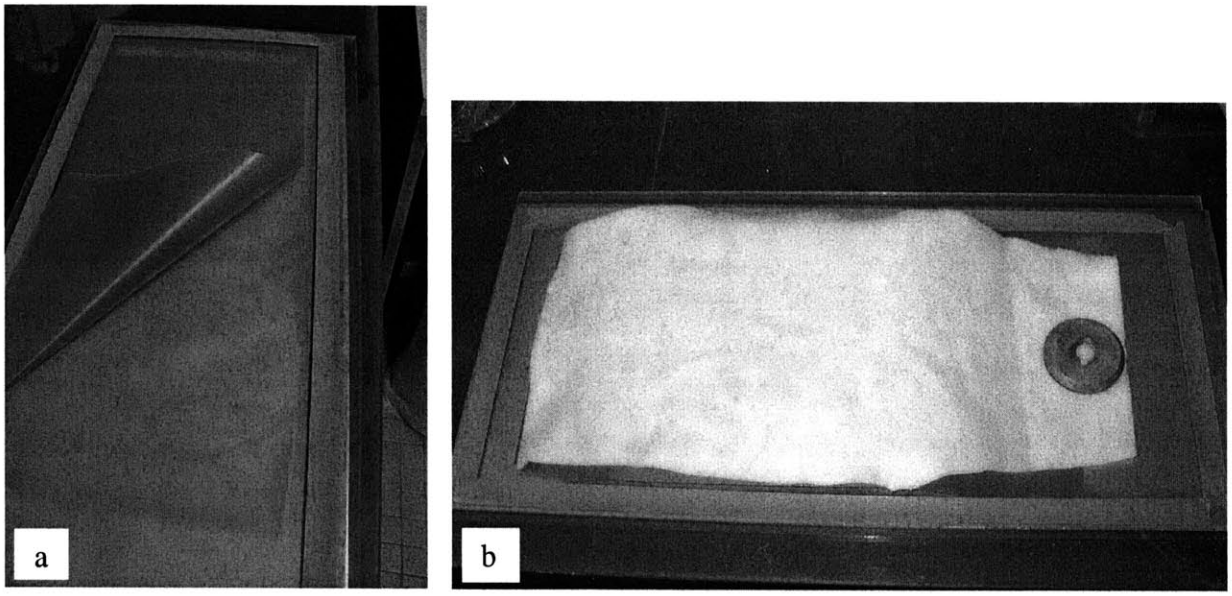

Figure 2: (a) Vacuum bagging initial layers. (b) Breather cloth and thru-bag connector.

2.2 High Temperature Exposure Testing

In order to examine the behavior of the laminates at high temperature two sets of five specimens were exposed to 200^{0}C and 400^{0}C for an hour. Both sets had high modulus carbon fibers as reinforcement. All the specimens were 2.1 mm thick and 25.4 mm wide. The core was the same for all of the panels (Grade 2 Titanium sheets).

After the specimens were made and cured as described before, they were placed in a furnace at room temperature. Then the furnace was turned on until the desired temperature was reached and turned off an hour after it reached this temperature. All specimens were tested at room temperature after a minimum of 24-hour cooling period.

Figure 3: Curing Setup

2.3 Testing

A total number of eighteen specimens were tested. Three of them were commercially pure grade 2 titanium strips. They were 25.4mm wide by 1.6mm deep and had a length of 200 mm. The remaining fifteen laminates have high modulus carbon fiber skins. The addition of the skins increased the thickness to 2.1 mm. The skins were made with a Geopolymer matrix and three high modulus carbon fiber tows. The properties of the carbon fiber tows used are provided in Table 1. The test matrix as well as specimen details are presented in Table 2.

Table 2: Test Matrix

Type of Test	Grade 2 Titanium	Room Temperature	After Exposure at 200°C	After Exposure at 400°C
Three point Bending	3 specimens 25.4x1.6x200mm (WxDxL)	5 specimens 25.4x2.1x200mm (WxDxL)	5 specimens 25.4x2.1x200mm (WxDxL)	5 specimens 25.4x2.1x200mm (WxDxL)

The flexural tests were conducted over a simply supported span of 140 mm with a center-point load in accordance with ASTM D790-93 (10) (Figure 4.). The specimens were 1.6 to 2.1 mm thick and 25.4 mm wide. This gave span to depth ratios between 87.5:1 and 67.5:1. Both of these values were within the acceptable range of the standard flexure test. The tests were conducted on an INSTRON Electromechanical Frame system under deflection control with a mid-span deflection rate of 14.5-20 mm/min. The mid-span deflection was measured using the cross head displacement of the testing frame and was verified using an LVDT. The instrumentation was used to obtain the load vs. deflection curves of the specimens. The 3 point bending tests were used to provide the behavior at the interlaminar level and the bending stiffness of the composite.

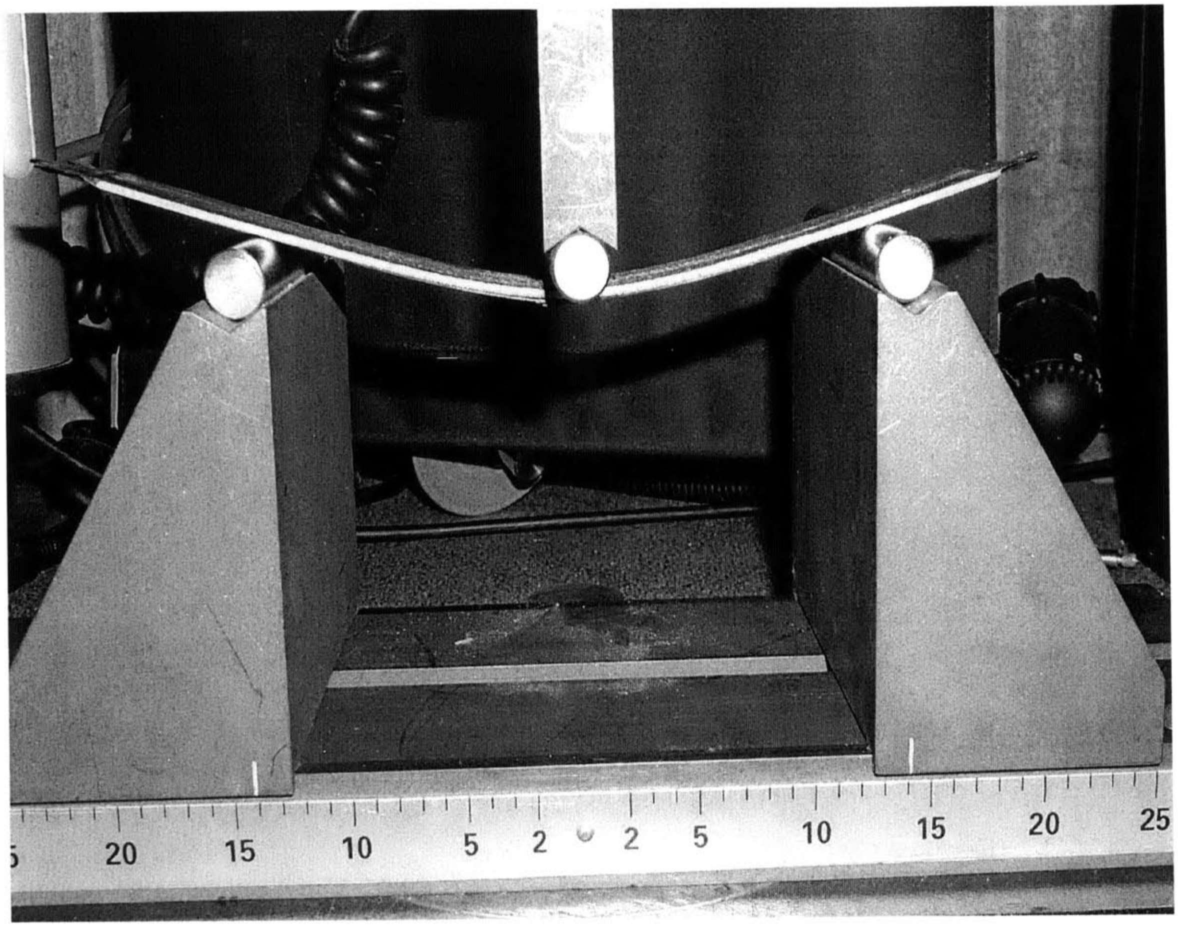

Figure 4: Testing setup

3. RESULTS AND DISCUSSION

The load versus deflection curves of the pure titanium specimens are shown in figure 5 while the load-deflection curves for non-heat treated specimens strengthened with carbon fibers are shown in figure 6. The strengthened specimens failed by fracture of the tensional reinforcement. The effect of the composite skins is shown in Figure 6. where, after the fracture of the reinforcement, there is a decrease in the recorded load; the remaining strength and the ductility are provided by the titanium core. No delamination was observed before the fracture of the fibers. The flexural curves for specimens subjected to 200^0C and 400^0C are presented in figures 7 and 8 respectively. All load deflection curves exhibit the same ductile behavior as the pure titanium samples. The specimens failed in the same manner as the specimens that were not subjected in high temperature. A comparison of load-deflection curves for all type of specimens is shown in figure 9. In this figure, "Titanium" refers to pure titanium specimens, "HMCF" to high modulus carbon fiber strengthened specimens, "HMCF-200C" to specimens strengthened with carbon fibers subjected to 200^0C for an hour, and "HMCF-400C" to specimens strengthened with carbon fibers subjected to 400^0C for an hour. It is evident from the graphs that the pure titanium specimens exhibited lower strength and stiffness compared to the specimens strengthened with high modulus carbon tows. The exposure to 200^0C had a very small effect on the mechanical properties of the specimens. The ultimate load remained at a level of 230 N to 240 N. On the contrary, the specimens stiffness was slightly reduced. The carbon fiber skins performed very well due to the protection provided by the fireproof matrix. Specimens that were subjected at 400^0C performed also very well. A small decrease of the ultimate load was observed at a level of approximately 10 percent. The stiffness of the specimens is almost the same as the one from specimens subjected at 200^0C. The reduction of strength can be explained by the fact that some of the fibers oxidized at 400^{0}C. All specimens exhibited failures that were driven by the fracture of the fibers on the tension face (figure 10a). The fact that no failure was recorded due to delamination presents a very interesting finding. The bond between the composite skins and the titanium core is strong and the use of Geopolymer as a material can be characterized as successful.

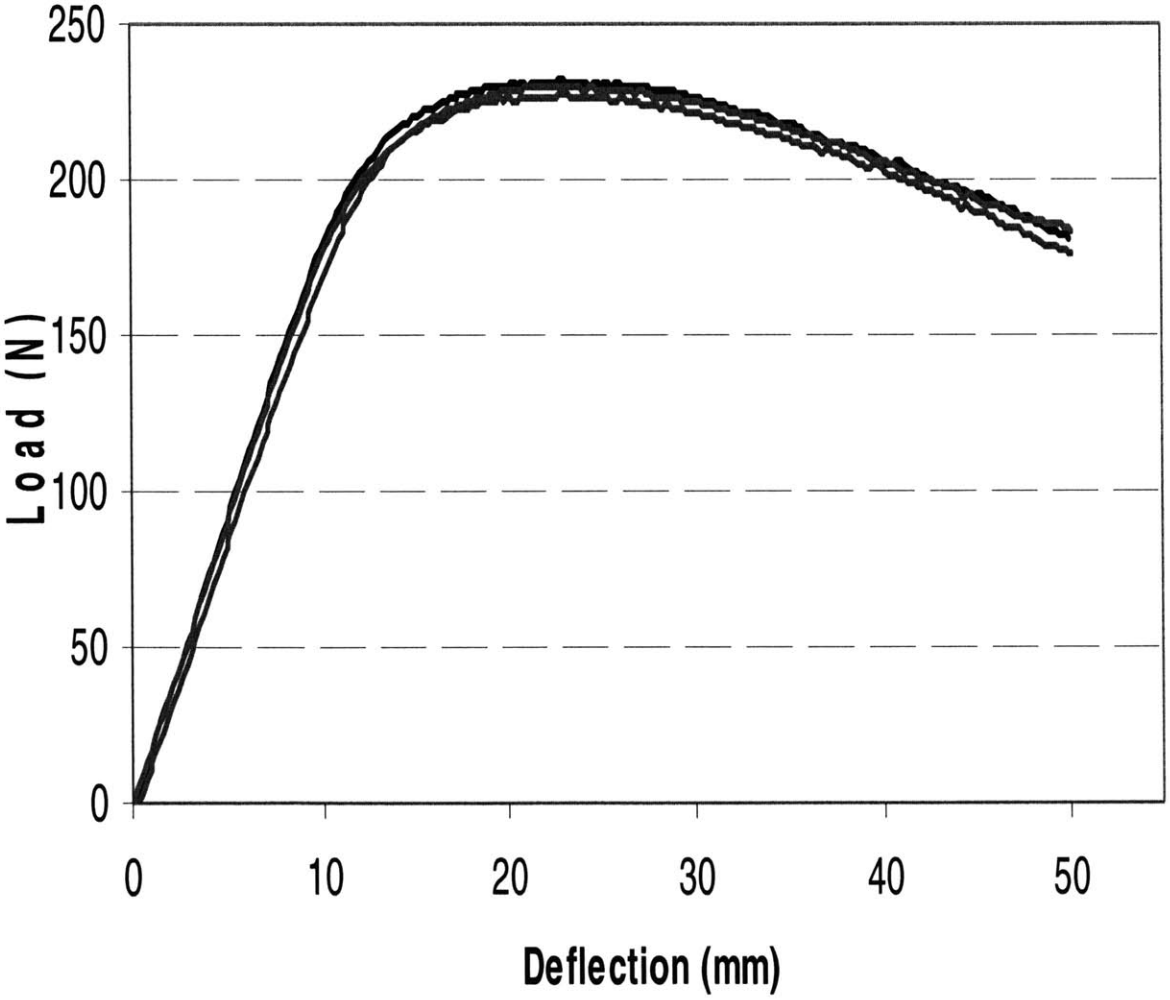

Figure 5: Load vs. Deflection curves of titanium specimens tested in 3-point bending

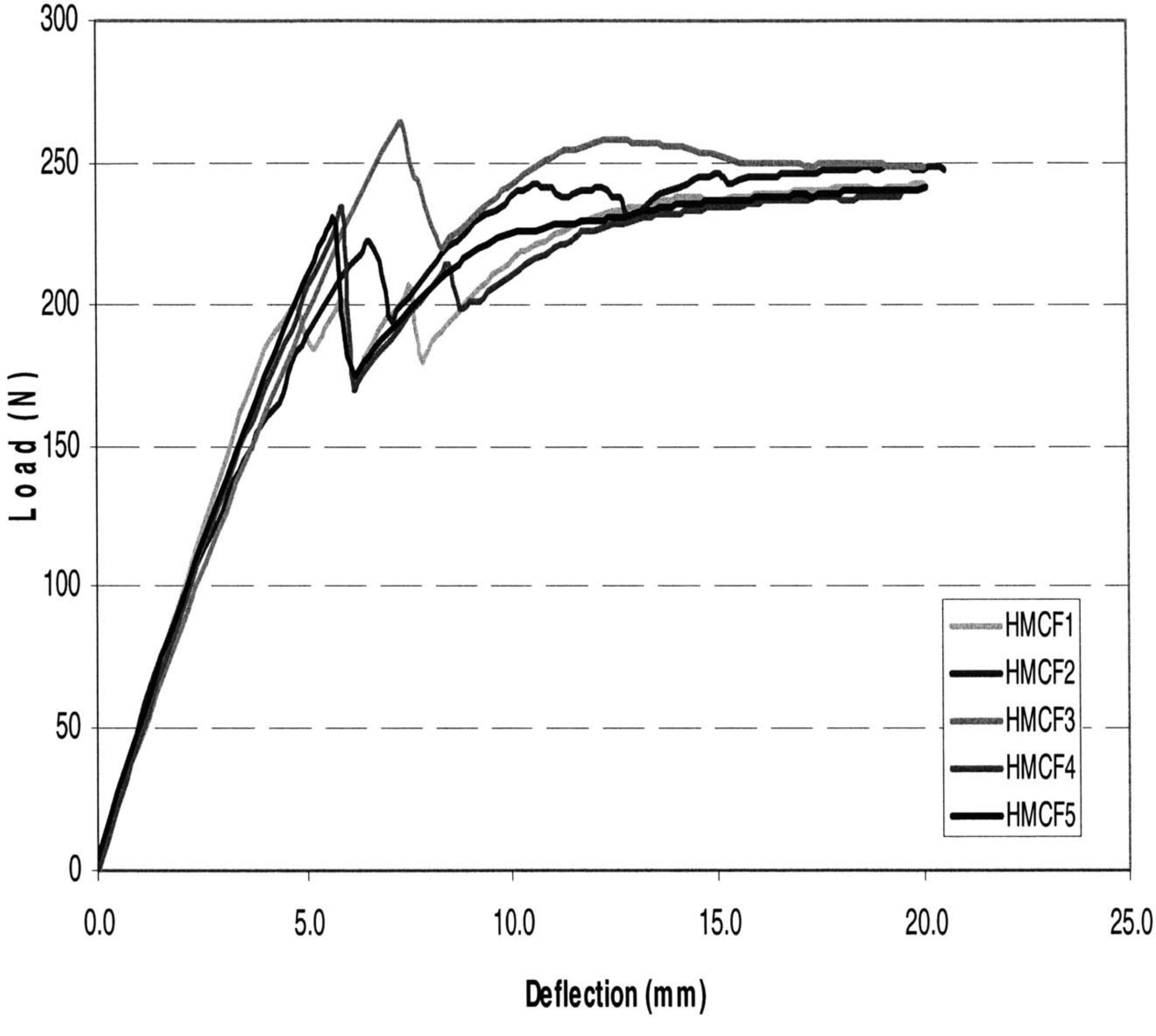

Figure 6: Load vs. Deflection curves of HMCF specimens tested in 3-point bending

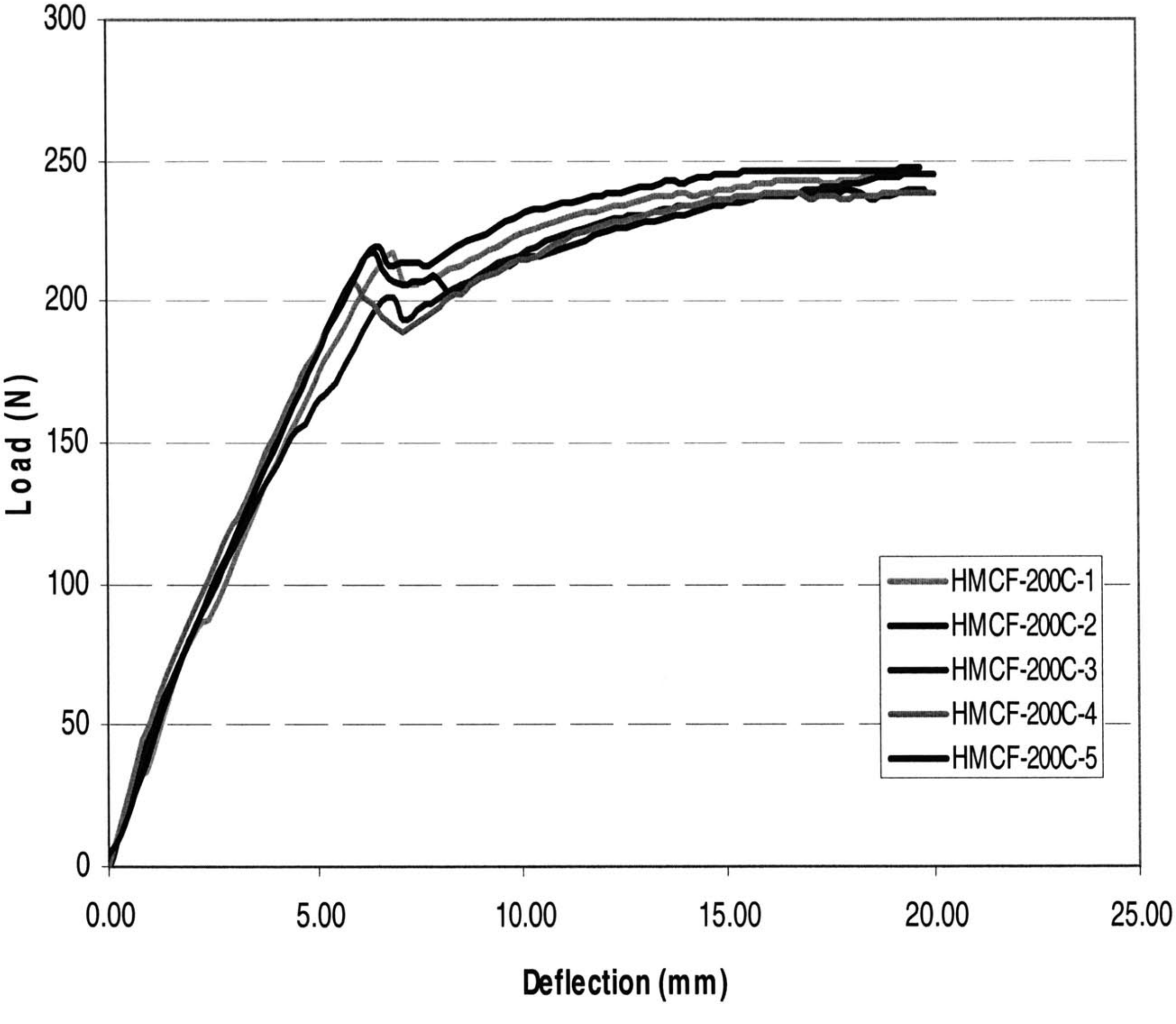

Figure 7: Load vs. Deflection curves of HMCF specimens tested in 3-point bending after exposure at 200^0C for an hour

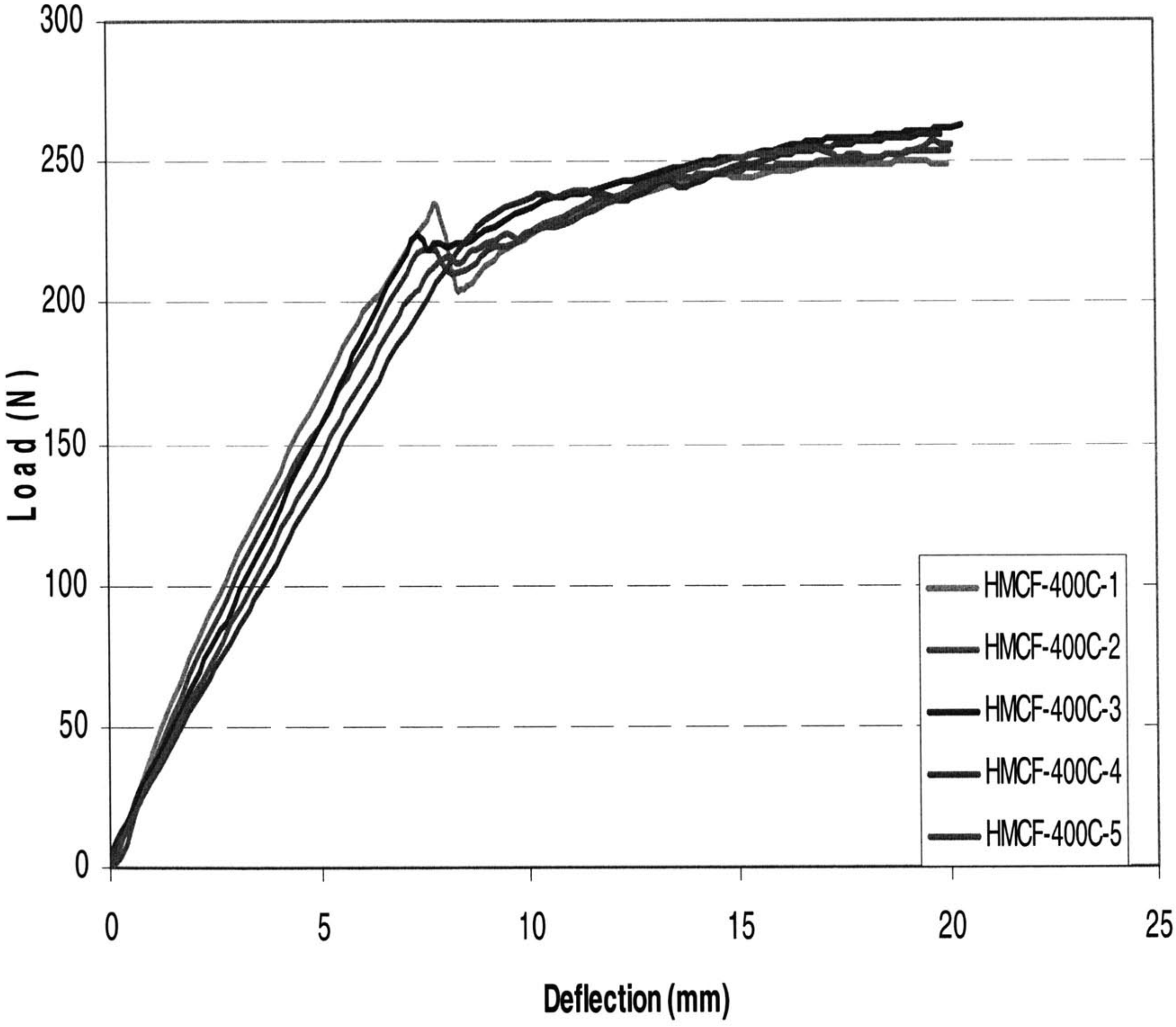

Figure 8: Load vs. Deflection curves of HMCF specimens tested in 3-point bending after exposure at 400^0C for an hour

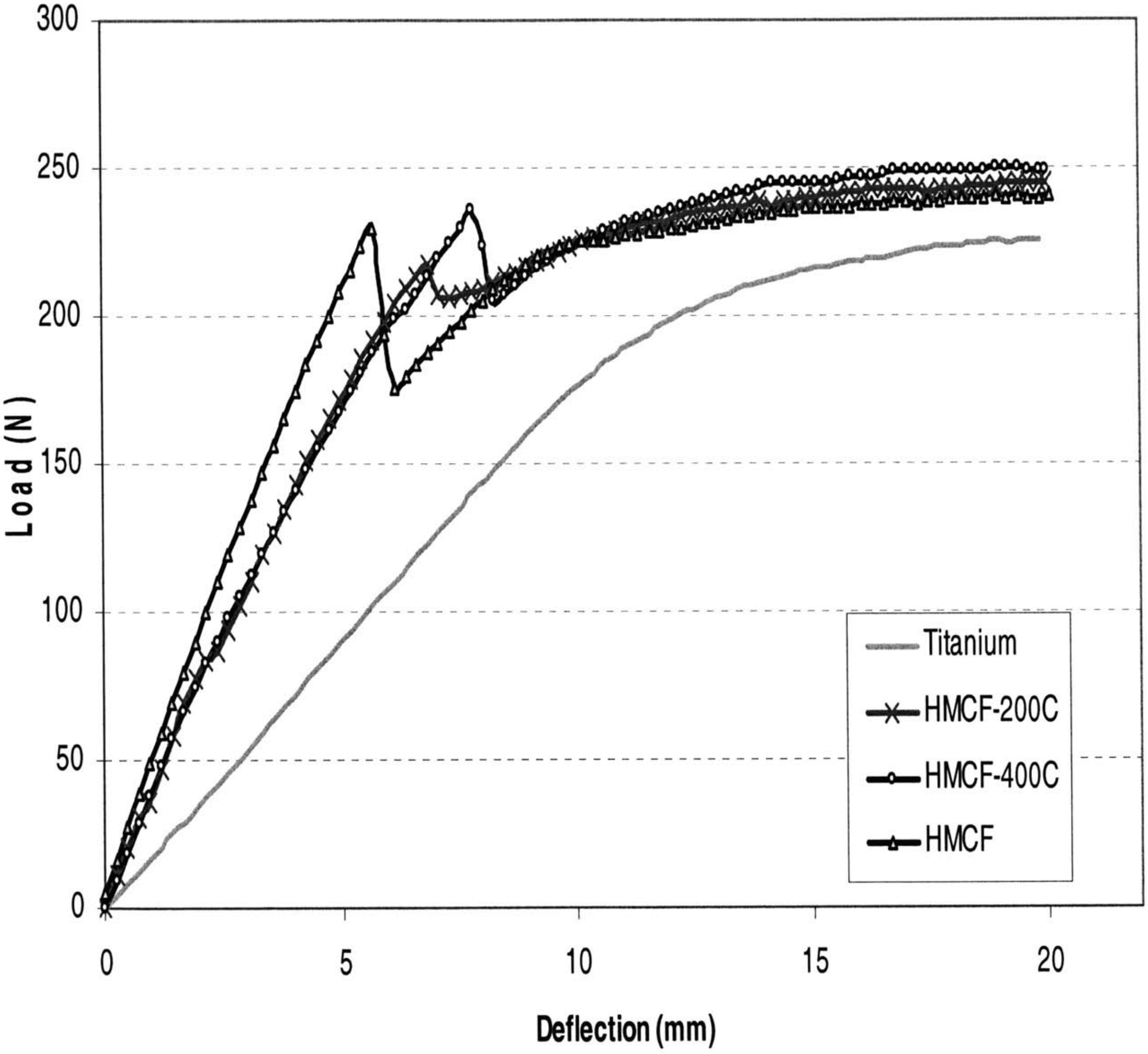

Figure 9: Load vs. Deflection curves of specimens tested in 3-point bending tests after exposure at different temperatures

Classical bending theory was used to calculate the stiffness of the specimens. The titanium had a modulus of elasticity of approximately 110 GPa while the strengthened specimens exhibited a modulus of 150 GPa. The increase of stiffness was not as high as anticipated. It is believed that better fiber alignment and less damage during impregnation would result in much better performance of the reinforcement. A possible use of a unidirectional fabric instead of tows will provide better control of the fiber orientation.

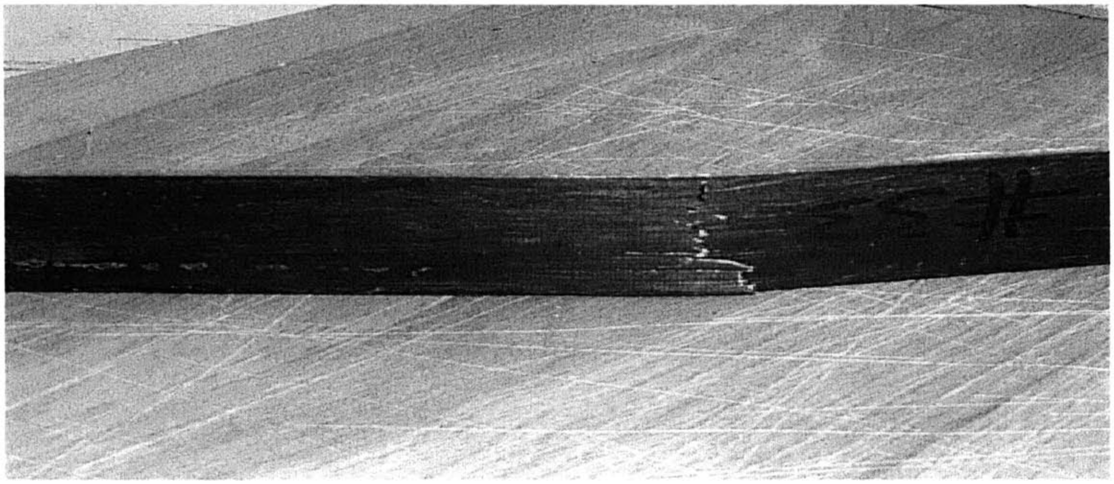

Figure 10: (a) Fractured fibers in tension face.

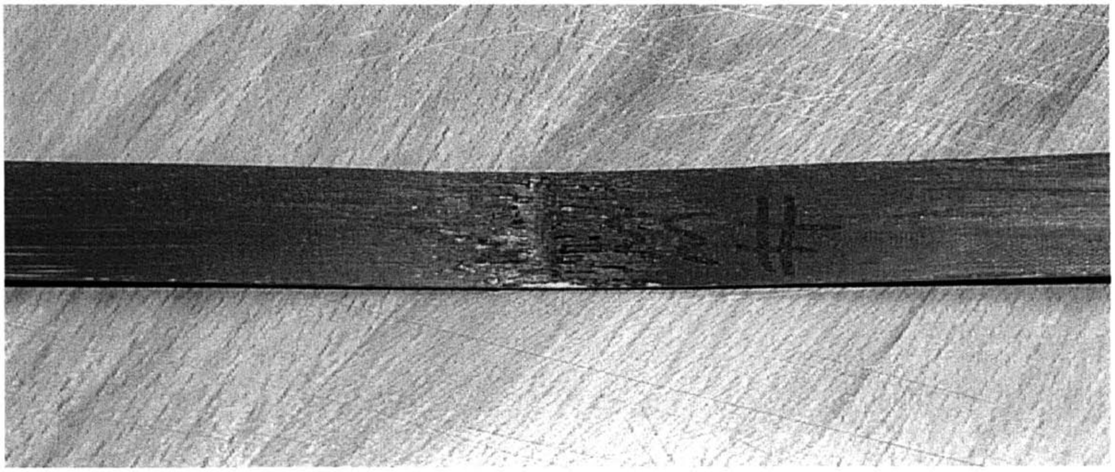

Figure 10: (b) Crushed fibers at load application point in compression face.

Another observation is that the reinforcement on the compressive side of the slabs was crushed at the points were the load was applied (figure 10b). This might have affected the stiffness of the specimens. Due to the location of the failure it was impossible to detect if the failure on the compressive side happened before the failure of the reinforcement in the tension side. During the duration of the experiments no visual sign of crushing was identified. It should be noted, that no delamination or bulking of the compressive reinforcement took place. It is believed that more experiments need to be conducted in order to verify the failure sequence. It should also be noted that load vs. deflection curves for all tested beams were linear up to the fracture of the tension reinforcement. After this point the laminate behaved exactly like the pure titanium specimens.

4. COMPARISON

Titanium is lightweight, strong, and has very high melting point. To show that titanium is the great material for applications such as airplane structures, space vehicles, chemical processing equipment, marine components, aircraft engine blades, and rocket motor cases, the comparisons with common structural materials such as steel and aluminum are taken. Steel is the most common material for structural application. It has very high tensile strength. However, it is also heavy. As performance demands increase, so do the demands for increased mechanical performance, such as increased strength and fracture toughness, at reduced overall weight. Reduced weight can be most efficiently realized by the use of light (low-density) metals, such as aluminum and titanium (11). Aluminum is very light, but it has low tensile strength, and very low modulus and melting point, which are the constraints for numerous applications. The ability to increase Young's Modulus of elasticity without increasing weight makes carbon fiber/titanium laminates an attractive alternative.

4.1 Physical Properties

Firstly, we need to understand the different physical properties of titanium, steel, and aluminum. Table 3 shows the density, melting point, Young's Modulus of elasticity, and thermal expansion coefficient of the three materials. The density of titanium is only 57% of steel, and the Young's Modulus of elasticity of titanium is 66% greater than aluminum. This melting point is approximately 300°C above the melting point of steel and approximately 1100°C above that of aluminum.

Table 3: Physical Properties of different materials (1-3)

	Density, ρ	Melting Point	E/ρ	Thermal Expansion Coeff.
	(kg/m^3)	$(^\circ C)$	$(MPa)/(kg/m^3)$	$(m/m.K \times 10^{-6})$
Titanium	4500	1670	24.4	8.2
Steel	7850	1300	25.4	17.3
Aluminum	2700	660	25.9	22.2

4.2 Specimens' Sizes and Masses

The ultimate load and Young's Modulus of elasticity of the pure titanium and carbon fiber/titanium laminate sheets were obtained by using the three-point bending testing method. The specimen size shows in Table 4. Since the carbon fiber is very light, the assumption of without changing the specimen mass was made. Based on the above assumption, the density of the carbon fiber/titanium laminate is slightly lower than the pure titanium, approximately reduced by 7%. The area moment of inertias are calculated as well and shows in the table below.

The equation that used is: $I = bh^3/12$.

Table 4: Specimen Dimensions

	Width, b	Depth, h	Length, L	Density	Mass	I
	(cm)	(cm)	(cm)	(g/cm^3)	(kg)	(cm^4)
Pure Titanium	2.54	0.16	20	4.5	0.036576	0.000867
Carbon Fiber/Titanium Laminate	2.54	0.17	20	4.2	0.036576	0.001040

4.3 Load vs. Deflection

4.3.1 In Room Temperature

The applied load and maximum displacement relationships at room temperature for pure titanium, carbon fiber/titanium laminate, steel, and aluminum specimens are shown in Table 5 to Table 8. The load vs. deflection curves for the four different materials show in Figure 11. The calculation for the maximum displacement is done by using the equation (delta)$_{max}$ = $PL^3/48EI$.

In Figure 11 shows that steel has the highest stiffness; titanium is less stiff than steel, and Aluminum has the lowest stiffness. The carbon fiber/titanium laminate is slightly less stiff then steel and is stiffer than the pure titanium specimen.

Table 5: Applied Load and Max. Displacement of Pure Titanium

Applied Load, P	Length	E	I	Max. Displacement
(N)	(m)	(GPa)	(m^4)	(m)
0	0.20	110	8.67E-12	0
20	0.20	110	8.67E-12	0.0035
40	0.20	110	8.67E-12	0.0070
60	0.20	110	8.67E-12	0.0105
80	0.20	110	8.67E-12	0.0140
100	0.20	110	8.67E-12	0.0175
120	0.20	110	8.67E-12	0.0210
140	0.20	110	8.67E-12	0.0245
160	0.20	110	8.67E-12	0.0280
180	0.20	110	8.67E-12	0.0315
200	0.20	110	8.67E-12	0.0350

Table 6: Applied Load and Max. Displacement of Carbon Fiber/Titanium Laminate

Applied Load, P	Length	E	I	Max. Displacement
(N)	(m)	(GPa)	(m^4)	(m)
0	0.20	150	1.04E-11	0
20	0.20	150	1.04E-11	0.0021
40	0.20	150	1.04E-11	0.0043
60	0.20	150	1.04E-11	0.0064
80	0.20	150	1.04E-11	0.0085
100	0.20	150	1.04E-11	0.0107
120	0.20	150	1.04E-11	0.0128
140	0.20	150	1.04E-11	0.0150
160	0.20	150	1.04E-11	0.0171
180	0.20	150	1.04E-11	0.0192
200	0.20	150	1.04E-11	0.0214

Table 7: Applied Load and Max. Displacement of Steel

Applied Load, P	Length	E	I	Max. Displacement
(N)	(m)	(GPa)	(m^4)	(m)
0	0.20	200	8.67E-12	0.0000
20	0.20	200	8.67E-12	0.0019
40	0.20	200	8.67E-12	0.0038
60	0.20	200	8.67E-12	0.0058
80	0.20	200	8.67E-12	0.0077
100	0.20	200	8.67E-12	0.0096
120	0.20	200	8.67E-12	0.0115
140	0.20	200	8.67E-12	0.0135
160	0.20	200	8.67E-12	0.0154
180	0.20	200	8.67E-12	0.0173
200	0.20	200	8.67E-12	0.0192

Table 8: Applied Load and Max. Displacement of Aluminum

Applied Load, P	Length	E	I	Max. Displacement
(N)	(m)	(GPa)	(m^4)	(m)
0	0.20	70	8.67E-12	0
20	0.20	70	8.67E-12	0.0055
40	0.20	70	8.67E-12	0.0110
60	0.20	70	8.67E-12	0.0165
80	0.20	70	8.67E-12	0.0220
100	0.20	70	8.67E-12	0.0275
120	0.20	70	8.67E-12	0.0330
140	0.20	70	8.67E-12	0.0384
160	0.20	70	8.67E-12	0.0439
180	0.20	70	8.67E-12	0.0494
200	0.20	70	8.67E-12	0.0549

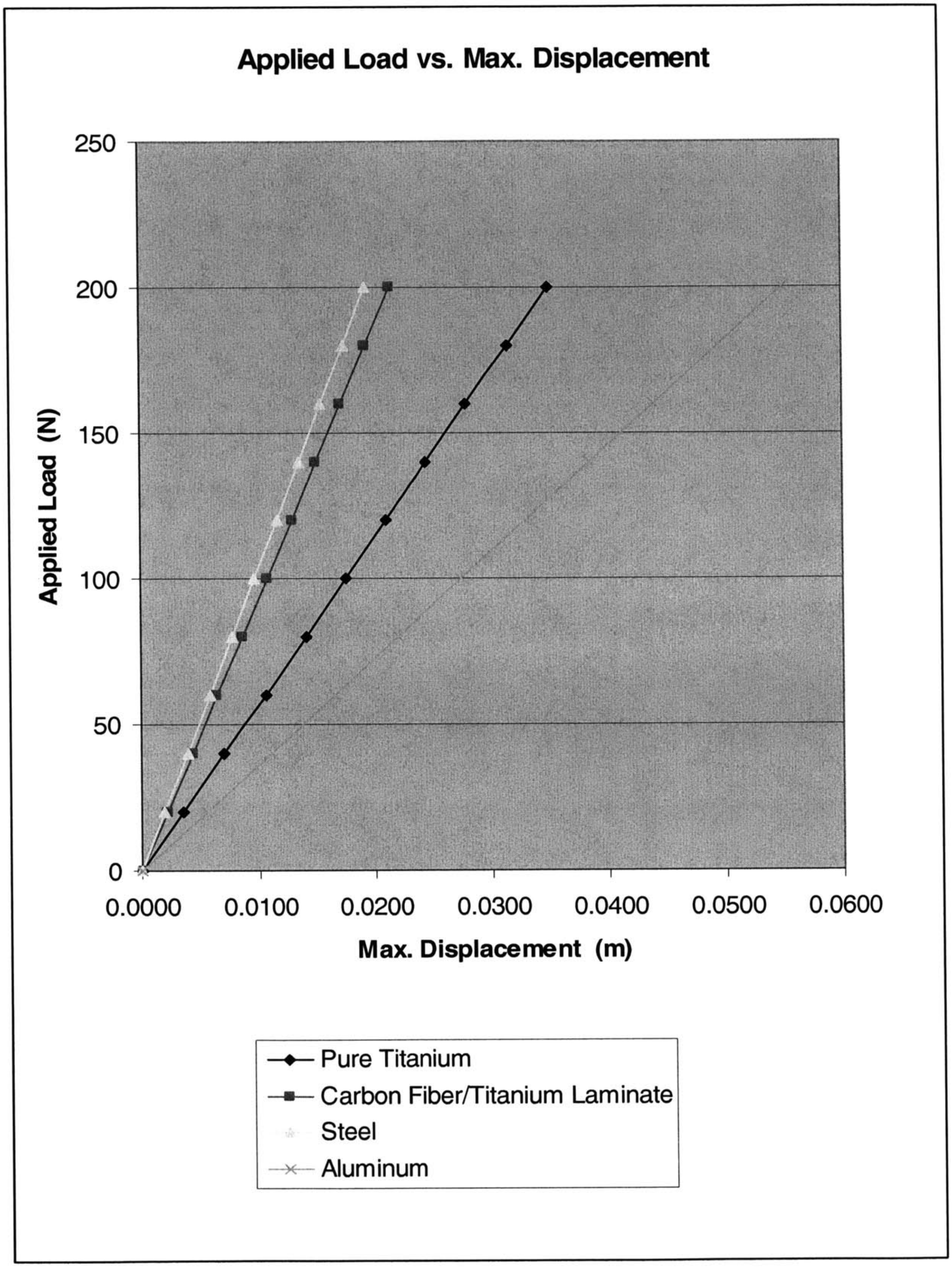

Figure 11: Applied Load vs. Max. Displacement

4.3.2 Specimens Subjected to 400°C (673K)

The previous results show that the exposure to 400°C had a very small effect on the mechanical properties of the specimens of titanium and carbon fiber/titanium laminate. Therefore, the assumption of very small change in dimension for titanium and carbon fiber/titanium laminate specimens is made. Since steel and aluminum have a lower melting point than titanium, the deformations that are caused by a change in temperature on steel and aluminum specimens must be determined. Table 9 shows the changes in dimensions in the x, y, and z directions for steel and aluminum specimens. In addition, Table 10 shows the new dimensions and the area moment of inertia of specimens of the materials.

Then the procedures in 4.3.1 are repeated. For the temperature of exposure to 400°C from room temperature, the applied load and maximum displacement relationships for steel and aluminum specimens are shown in Table 11 to Table 12. The load vs. deflection curves for specimens of the four different materials at room temperature and specimens of steel and aluminum at 400°C are showed in Figure 12.

The graph of steel at 400°C slightly moves to the right from the original one. The aluminum graphs for 400°C also moves to the right. This means that the stiffness of the two materials decreases as the temperature increases. The figure also shows that the aluminum graph moves more than in the way the steel graph moves. It is reasonable because aluminum has a lower melting point and higher temperature coefficient of expansion factor than steel.

This analysis proves that as the temperature increases, the steel and aluminum specimens become less stiff, and therefore, the materials are getting easier to reach their yield point and fail. Since titanium has high melting point, its mechanical properties will not have a lot of effect on temperature change of within 1000°C. Its thermal deformation is only about 0.8% of the length.

Table 9: Changing in Dimensions in the x, y, and z Directions

Room Temp. =	23	°C				
Final Temp. =	400	°C				
Material	δ_{xx}	ε_{xx}	ε_{yy}	δ_{yy}	ε_{zz}	δ_{zz}
	(m)	(m/m)	(m/m)	(m)	(m/m)	(m)
Steel	0.00130	0.00652	-0.00217	-0.00006	-0.00217	-0.000004
Aluminum	0.00167	0.00837	-0.00279	-0.000075	-0.00279	-0.000005

Table 10: New Dimension and Area Moment of Inertia of Specimen

	Width	Depth	Length	Density	Mass	I
	(cm)	(cm)	(cm)	(g/cm^3)	(kg)	(cm^4)
Pure Titanium	2.54	0.16	20	4.5	0.036576	0.000867
Fiber/Titanium Laminate	2.54	0.17	20	4.2	0.036576	0.001040
Steel	2.534	0.1596	20.0013	7.85	0.063806	0.000858
Aluminum	2.532	0.159	20.0017	2.70	0.021946	0.000848

Table 11: Applied Load and Max. Displacement of Steel (400°C)

Applied Load, P	Length	E	I	Max. Displacement
(N)	(m)	(GPa)	(m^4)	(m)
0	0.200013	200	8.58E-12	0.0000
20	0.200013	200	8.50E-12	0.0020
40	0.200013	200	8.50E-12	0.0039
60	0.200013	200	8.50E-12	0.0059
80	0.200013	200	8.50E-12	0.0078
100	0.200013	200	8.50E-12	0.0098
120	0.200013	200	8.50E-12	0.0118
140	0.200013	200	8.50E-12	0.0137
160	0.200013	200	8.50E-12	0.0157
180	0.200013	200	8.50E-12	0.0177
200	0.200013	200	8.50E-12	0.0196

Table 12: Applied Load and Max. Displacement of Aluminum (400°C)

Applied Load, P	Length	E	I	Max. Displacement
(N)	(m)	(GPa)	(m^4)	(m)
0	0.200017	70	8.48E-12	0
20	0.200017	70	8.48E-12	0.0056
40	0.200017	70	8.48E-12	0.0112
60	0.200017	70	8.48E-12	0.0169
80	0.200017	70	8.48E-12	0.0225
100	0.200017	70	8.48E-12	0.0281
120	0.200017	70	8.48E-12	0.0337
140	0.200017	70	8.48E-12	0.0393
160	0.200017	70	8.48E-12	0.0449
180	0.200017	70	8.48E-12	0.0506
200	0.200017	70	8.48E-12	0.0562

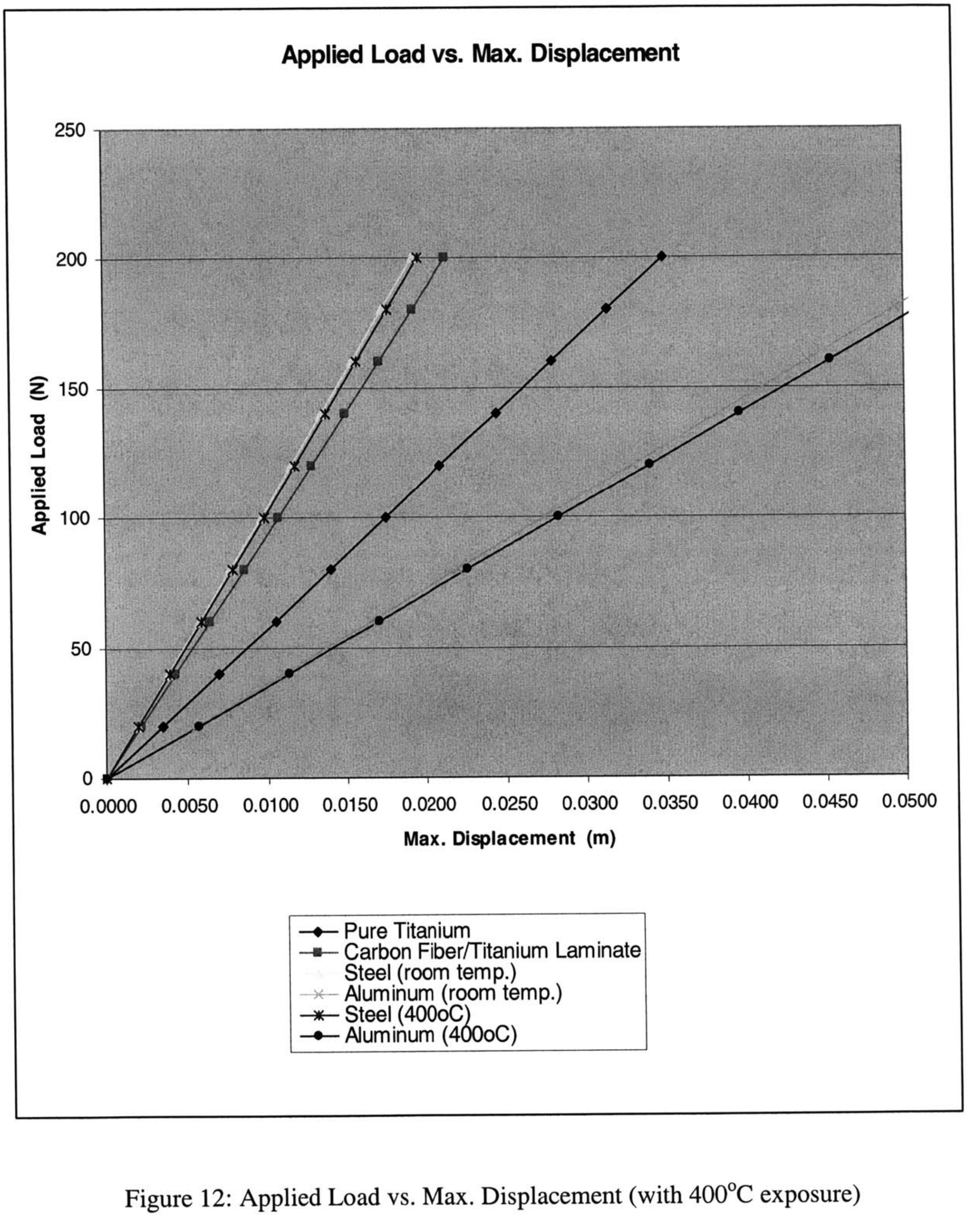

Figure 12: Applied Load vs. Max. Displacement (with 400°C exposure)

4.3.3 Rearrangement of Specimens' Size

Assuming the steel specimen after exposed to 400°C has the same stiffness as the carbon fiber/titanium laminate specimen. By increasing the thickness from 0.16cm to 0.225cm, the aluminum specimen will achieve the same stiffness as well.

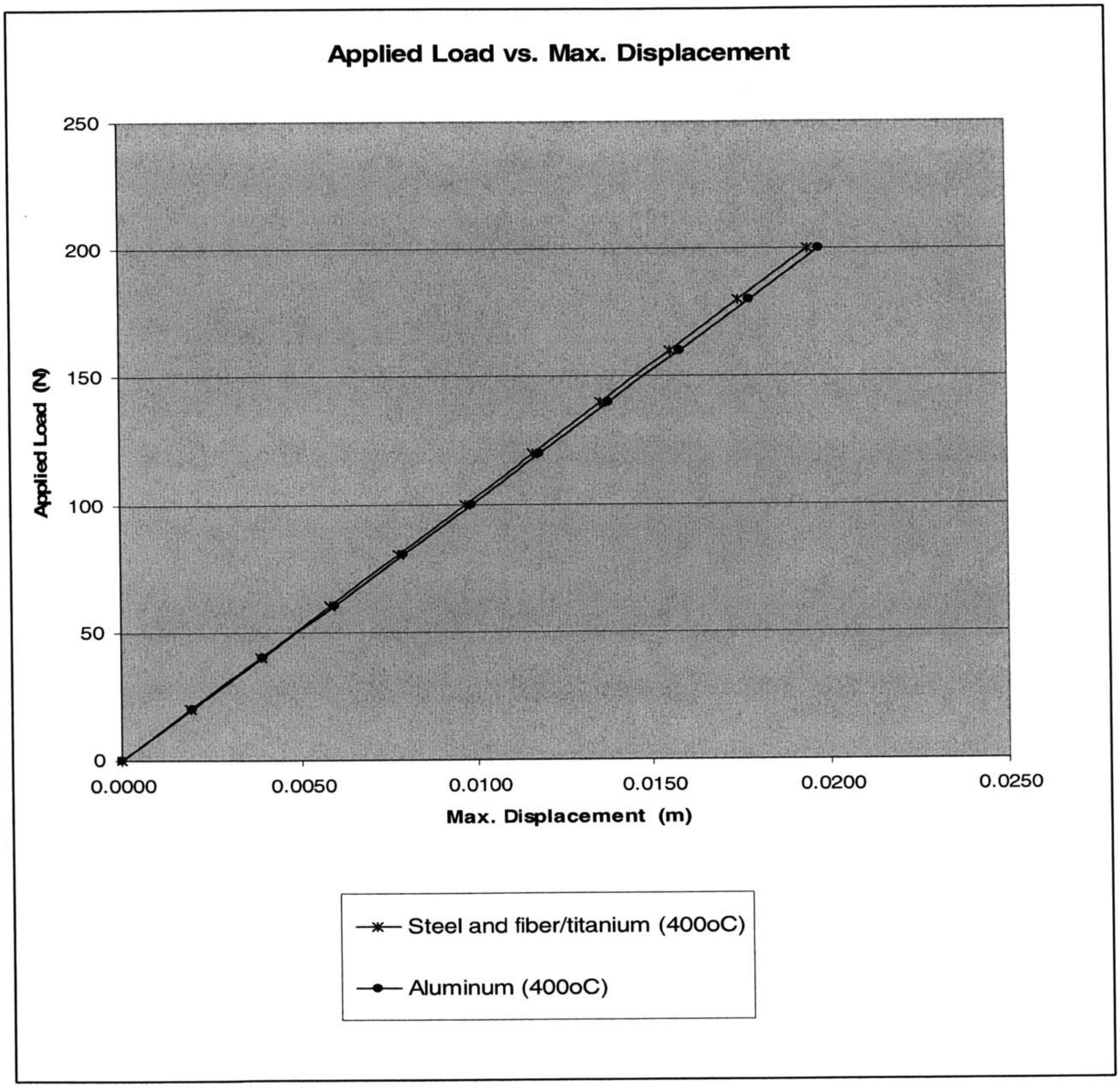

Figure 13: Applied Load vs. Max. Displacement (with 400°C exposure and different dimensions)

4.4 New Dimensions and Cost

For achieving with the same stiffness of the three different materials, the size of the specimen is needed to be rearranged. The new dimensions are showed in Table 13. The unit price of titanium is very expensive, about twenty-five dollars per kilogram, which is about 8 times of the unit price of steel and aluminum. Even though the modulus of elasticity of titanium was increased by fabricating with carbon fiber, the cost for such of a specimen of titanium is still very high compare to the steel specimen and the aluminum specimen. In order to lower the cost, the modulus of elasticity of the carbon fiber/titanium laminate needs to be increased further.

Table 13: Cost of the specimens (4, 5)

Material	Width	Depth	Length	Density	Mass	Cost	Total Cost
	(cm)	(cm)	(cm)	(g/cm^3)	(kg)	(\$/kg)	(\$)
Steel	2.54	0.16	20	7.85	0.0638048	3.50	0.22
Carbon Fiber/Titanium Laminate	2.54	0.17	20	4.24	0.036576	25.00	0.91
Aluminum	2.54	0.225	20	2.7	0.030861	3.00	0.09

5. CONCLUSIONS

Using the analysis of the results presented in this paper and observations made during fabrication and testing, the following conclusions can be drawn:

- It is feasible to fabricate laminates using a titanium core and inorganic matrix-carbon composite.
- High modulus carbon tows can be attached to the titanium core using Geopolymers.
- In all cases, the failure occurs by fracture of carbon in the tension face.
- No delamination of the composite skins was observed.
- The strength degradation is negligible up to 400^0C.
- The stiffness of specimens subjected at elevated temperatures was slightly reduced.
- The titanium plate increased stiffness by fabricating with high modulus of carbon fiber.
- Better fiber alignment and less damage during impregnation will result in much better performance of the reinforcement.
- Achieving in better result means having higher modulus of elasticity and stiffness. Therefore, the material (carbon fiber/titanium laminate) that used can be reduced for the same manner, which is resulted in less cost.
- Having low density, a high melting point, and high tensile strength compare to pure titanium, steel, and aluminum, carbon fiber/titanium laminate will be the perfect material for numerous application.

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