Nonlinear finite element analysis of thermoplastic railroad bridge

Rajai Z Al-Rousan¹,², Nadim I Shbeeb¹ and Rund Al-Masri¹

Abstract
Due to the environmental and financial benefits of thermoplastic materials as mentioned in literature and being a viable green solution, a nonlinear finite element analysis was conducted to study the behavior of thermoplastic materials of the No. 3 Fort Eustis railroad bridge using ABAQUS in terms of deflection, stress, and vertical forces at critical locations. Six models were simulated. These models were evaluated under GE 80-Ton switcher at 8 km/h (kph) speed and GP 16-120 Ton locomotives at speeds of 8, 24, 40, 56, and 80 kph. The models were validated against experimental results available in the literature. The models studied the effect of train speed on the deflection profile, flexural stress profile, vertical force profile, and stress profile along the bridge as well as the stress profile along the section. Based on the simulated models, it is clearly shown that the thermoplastic material has lower deflection and stress than wood; higher speeds resulted in lower stress and deflection. Based on this study, thermoplastic material can be considered as a good alternative because of its performance in terms of stress, vertical force, and corresponding deflection.

Keywords
Nonlinear finite element analysis, thermoplastic, railroad, simulated, bridge, deflection, stress, vertical force

Introduction
The loss of structural integrity of existing steel, timber, and reinforced concrete bridges due to corrosion and biodegradation has been a major issue in the world. The estimated

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cost of repair and replacement in the United States alone is estimated to be around US$300 billion per year.\textsuperscript{1} Every year about 10–15 million wood railroad crossties are replaced as they do not perform well in a wet environment.\textsuperscript{2} Moreover, the prices of wood will rise due to the laws and policies that protect trees and forests.\textsuperscript{3} The need for new advanced materials has become a necessity. This new material when compared to conventional materials such as steel, concrete, and wood should be more durable, sustainable, should accelerate construction, and be environmentally friendly. Such a material is enhanced reinforced structural plastic composite (RSPC). RSPC is an immiscible polymer blend (IMPB) with reinforcing agents such as polypropylene- or polystyrene-coated glassed fiber merged within the recycled plastic lumber matrix and it is made of nearly 100\% recycled postconsumer and industrial plastics. RSPC is maintenance free (corrosion, insect, and rot resistant) for at least 50 years.\textsuperscript{4}

It is environmentally friendly as it does not leach toxin chemicals into soil or water and reduces deforestation and green house gases. It has high-energy absorption capacity and is recyclable.\textsuperscript{5,6} These prefabricated light-weight materials can be molded in any shape and readily transported to construction sites, thus expediting the construction time.\textsuperscript{7} In May 1997, The Facility for Accelerated Service Testing (FAST) track at the American Association of Railroads (AAR) and Transportation Technology Center in Pueblo, Colorado, installed 24 plastic/composite crossties. In February 1998, a second batch of 24 plastic/composite crossties were installed in Fast track. By April 1999, the first batch of crossties was subjected to 182 million gross tons (MGT) and the second batch was subjected to 108 MGT. After visual inspection at that time, no deterioration was observed.\textsuperscript{8} AAR (December, 1998) constructed plastic ties in No. 10 turnout (switch) at Naval Surface Warefare Center in Crane, Indiana, USA. This was the first project to utilize plastic ties in turnout.\textsuperscript{9} New York City Department of General Devices constructed the first plastic lumber civil structure of major significance, the Tiffany Street pier, located at the end of Tiffany Street in the Bronx in New York City, USA. The recreation pier is 125 m long and 15 m wide. This structure includes plastic lumber pilings, timber joists, and railings.\textsuperscript{10} United State Army (1998) constructed the first thermoplastic (PS/HDPE) vehicular bridge at Fort Leonard, Missouri, USA, the 24-foot span bridge was designed by M. G. McLaren Consulting Engineers, with maximum load capacity of 29,430 kg. The decadent deck was replaced by a new thermoplastic deck with rectangular cross section supported by the existing steel girders; it shows no sign for degeneration and requires no maintenance even after 13 years. The bridge was built with initial high cost, which was recovered within the first 8 years of its life.\textsuperscript{11}

United State Army (2010) decided to replace two railroad timber bridges at Fort Eustis, Virginia, USA, to be the world’s first thermoplastic railroad bridges. All the components of both bridges including girders, pier caps, pilings, and crossties are made from thermoplastic (FRPP/HDPE) material, but for economic reasons the existing abutments were retained. Bridge No. 3 consists of four spans with 11.73 m total length and bridge No. 7 consists of eight spans with approximately 25.6 m total length, designed to carry the Cooper E60 load and the 1156 kN alternate live load on four axles to have a maximum load capacity of 127,530 kg. Live load testing was carried out on the bridge
using several railway vehicles and speeds, including a GE 80-Ton (72,574.8 kg) switcher and a GP 16-120 Ton (117,000 kg) locomotives. The vehicles passed over the bridges back and forth with speed ranging from 8 km/h (kph) to 40 kph. The speed was limited to 40 kph due to the curved tracks close to the bridge. The maximum deflection recorded was 5.33 mm compared to the allowable deflection of 5.5 mm (The US Army chose to limit the deflection to L/600\textsuperscript{12}). Also estimation for deflection was conducted using the LARSA program that is an advanced structural analysis program that is capable of performing moving loads.\textsuperscript{12} Recently, the US Army Engineer Research and Development Center conducted a load test on a thermoplastic composite bridge located on Tucker’s Road in North Carolina, USA. The bridge was made with 94\% recycled high-density polyethylene. The finite element analysis performed on the bridge based on the test data proved that the bridge exceeded design specifications.\textsuperscript{13} Another study tackled the strengthening of concrete column stubs by using resin-infused composite wraps. The study showed that the use of the composite wraps substantially increased both the load carrying capacity and deformation capability of the stubs.\textsuperscript{14} Other researcher focused on understanding the flexural behavior of thermoplastic beams, in which the ultimate strength design procedure was developed for thermoplastic beams.\textsuperscript{15}

Nonlinear finite element analysis

Six models were simulated using ABAQUS\textsuperscript{16} using two types of materials (thermoplastic and wood). These models were evaluated under GE 80-Tons switcher (GE80) at 8 kph speed and GP 16 120-Ton (GP16) locomotive with speeds of 8, 24, 40, 56, and 80 kph. The first stage aimed at validating the model by comparing the simulated models against the experimental results reported by Kim et al.\textsuperscript{12} Then the analysis was expanded to include the effect at higher speeds. Although the experimental study was limited to 40 kph due to the curved tracks close to the bridge, no such restrictions are present in the simulated models. Only one speed of 40 kph was chosen for the wood model for comparison with the thermoplastic material.

Description of the bridge

Figure 1(a) depicts the cross section of the bridge used in the models (Fort Eustis Bridge No. 3). The bridge consists of pile caps, bearing stiffeners, clusters of three 460 I-beams reinforced with horizontal and vertical stiffeners, block shears, a deck located above the 460 I beams, and crossties (Parsons Brinckerhoff 2011). Two rails are used with the inside distance between them equal to 1440 mm according American Railway Engineering and Maintenance-of-way Association (AREMA, 2014).\textsuperscript{17} The crossties dimensions were 250 × 250 mm\textsuperscript{2}.

Material parameters

Two types of material are used in the models for comparison reasons.
Thermoplastic material. Thermoplastic is a viscoelastic material. The mechanical properties are listed in Table 1. The stress–strain relationship, stress relaxation data, and normalized shear modulus versus time are shown in Figure 2. The stress relaxation test data (shown in Figure 2(b)) were used to estimate the shear modulus ($G(t)$) and the normalized shear modulus (shown in Figure 2(c), calculated at 40 h intervals). The normalized shear modulus, which is used in ABAQUS, is implemented through the use of Prony series. The instantaneous modulus $G_0$ and bulk modulus $K_0$ are determined from the modulus of elasticity and poison ratio provided in Table 1. The shear long-term modulus was assumed to be the one at the end of the shear modulus curve at time equal to 2160 h.

Figure 1. Cross-section and 3-D view of the model: (a) Cross-section of the model, all dimensions in millimeters; (b) Plan view of bridge, all dimensions in meter; (c) Fort-Eustis’ Railroad Bridge; and (d) 3-D model. 3-D: three-dimensional.
Wood material. Wood (White oak) was modeled as an orthotropic material. The mechanical properties are listed in Table 2.19

Table 1. Mechanical properties of thermoplastic material.18

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity (ASTM D6111)</td>
<td>0.85–0.90</td>
</tr>
<tr>
<td>Elastic modulus (ASTM D6108)</td>
<td>2413.2 MPa</td>
</tr>
<tr>
<td>Allowable tensile stress (ASTM D638)</td>
<td>4.14 MPa (ultimate = 20.68 MPa)</td>
</tr>
<tr>
<td>Allowable flexural stress (ASTM D6109)</td>
<td>4.14 MPa (ultimate = 17.24 MPa)</td>
</tr>
<tr>
<td>Allowable compressive stress (ASTM D695)</td>
<td>4.14 MPa (ultimate = 17.24–29.6 MPa)</td>
</tr>
<tr>
<td>Allowable shear stress (ASTM D6109)</td>
<td>2.41 MPa (ultimate = 10.34 MPa)</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (ASTM D696)</td>
<td>0.0000282 in/in/deg F</td>
</tr>
<tr>
<td>Density</td>
<td>881 kg/m³</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Figure 2. Mechanical properties of thermoplastic material.

Assembly of model

Figure 1 represents Fort-Eustis’s No. 3 railroad bridge that consists of four spans with a total length equal to 11.43 m.12 All parts of the bridge except the rails are made of
thermoplastic material. The model was built as shown in Figure 1(a). The different parts (mentioned in the description of the model earlier) were connected together through the tie constraint feature in ABAQUS. The tie constraint feature allows for the fusion of two regions together despite the fact that the meshes created on the surface of the different parts are dissimilar. Only half the bridge was modeled making use of symmetry along the longitudinal direction (z axis; Figure 1(d)). A quarter model could not be used due to the loading arrangement of the locomotives.

Each pile cap of the Fort-Eustis’s No. 3 railroad bridge is supported by six piles. The piles were not modeled in this study, instead and due to symmetry, three circular partitions were created at the bottom of each cap and treated as fixed boundary condition. Two types of trains were used as loads in the analysis, GE80 and GP16. The GE80 switcher is a diesel–electric locomotive model built by GE Transportation Systems. It is classified as a B-B–type wheel arrangement locomotive, meaning four wheels on each side with a diameter of 1.0 m the distance between the wheels (center to center) is 2.14 m. The distance between the centers of the wheel bases is 6.71 m. It was designed for industrial and light switching duties around railheads and ports with weight equal to 80 short tons. The GP16 is a series of rebuilt diesel–electric locomotives, a result of a remanufacturing program initiated by the Seaboard Coast Line Railroad in an effort to spare the cost of purchasing new motive power in the late 1970s. The GP16 is also classified as a B-B–type wheel arrangement locomotive with four wheels on each side with a diameter of 1.0 m, the distance between the centers of the last wheel to the first wheel is 6.71 m. The GE80 locomotive loads were modeled as four blocks that simulate the wheels of the train (Figure 1(d)). The dimensions of the block were 1.0 m in length and 0.5 m in height with a width equal to 0.25 m less than the width of the rail (0.3 m) to avoid any stress concentrations at the edges. The GP16 locomotive loads were modeled as two blocks (same dimensions as the GE80 blocks) that simulate the wheels of the train (Figure 1(d)). Only two wheels were needed for the GP16 since it’s longer than the bridge (17 m), as the last wheel of the front axle leaves the bridge the first wheel of the back axle enters. The rails were extended beyond the bridge to accommodate the length of the trains. Fixed boundary conditions were used for the extended rails. The surface to

<table>
<thead>
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<th>Table 2. Wood material’s twelve constant.19</th>
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<tbody>
<tr>
<td>Constant</td>
</tr>
<tr>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>Elastic modulus</td>
</tr>
<tr>
<td>$E_1$</td>
</tr>
<tr>
<td>$E_2$</td>
</tr>
<tr>
<td>$E_3$</td>
</tr>
<tr>
<td>Shear modulus</td>
</tr>
<tr>
<td>$G_{12}$</td>
</tr>
<tr>
<td>$G_{13}$</td>
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<tr>
<td>$G_{23}$</td>
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<tr>
<td>Poisson’s ratio</td>
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<tr>
<td>$\nu_{12}$</td>
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<tr>
<td>$\nu_{13}$</td>
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<td>$\nu_{21}$</td>
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<tr>
<td>$\nu_{31}$</td>
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<td>$\nu_{32}$</td>
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Al-Rousan et al. 855
surface interaction feature in ABAQUS was used to simulate the contact between the blocks (wheels) and ties.

The element type selected for the analysis was an eight-node linear brick incompressible mode element (designated in ABAQUS as C3D8I). This type of element is suited for flexural analysis and eliminates the development of any artificial energy. ABAQUS/Explicit was used for the analysis. Several convergence studies were conducted for the different speeds and materials. The optimum mesh was based on the thermoplastic material as it needed more elements for convergence than wood. At the end, 35,335 elements were selected for all the models. Figure 3 shows one of the convergence studies, while Figure 1(d) shows the mesh of the model.

**Results and discussion**

**Validation of NLFEA results**

The nonlinear finite element analysis (NLFEA) results were validated with the experimental test results reported by Kim et al.\textsuperscript{12} The maximum deflection obtained from the NLFEA and the experimental test results were in good agreement as shown in Table 3. The maximum error is equal to 7.0% for the GP16 train at a speed of 40 kph, while the minimum error of 0.3% was for the GE80 train at a speed of 8 kph. It should be pointed out that the piles were not modeled and considered as fixed-boundary condition, thus any axial deformation in the piles were not accounted for. It is also observed that the insensitivity of the LARSA results to speed since it does not count for the effect of speed.
Figures 4 and 5 show the wheel locations and naming convention at which the results were taken for the GP16 and GE80 locomotives, that is, F1-GP16 is when the front wheel of the GP16 locomotive is at a distance 1.90 m from the start of the bridge (at the middle of the first span). Figure 6(a) to (d) illustrates the deflection profile along the bridge for the GP16 locomotive at speeds of 8, 24, 40, 56, and 80 kph. It is evident that the deflection decreases with the increase of the speed and it’s more distinct at higher speeds. For safety reasons and other dynamic effects, this phenomenon is neglected by the AREMA codes. Figure 6(e) shows the deflection profile along the bridge for the GE80 at

### Table 3. Validation of NLFEA results.

<table>
<thead>
<tr>
<th>Model</th>
<th>NLFA $\Delta_{\text{max}}$ (mm)</th>
<th>Experiment $\Delta_{\text{max}}$ (mm)</th>
<th>LARSA $\Delta_{\text{max}}$ (mm)</th>
<th>%Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE80 (8 kph)</td>
<td>4.483</td>
<td>4.496</td>
<td>6.401</td>
<td>0.295</td>
</tr>
<tr>
<td>GP16 120 (8 kph)</td>
<td>5.752</td>
<td>5.410</td>
<td>6.401</td>
<td>6.322</td>
</tr>
<tr>
<td>GP16 120 (24 kph)</td>
<td>5.401</td>
<td>5.055</td>
<td>6.401</td>
<td>6.845</td>
</tr>
<tr>
<td>GP16 120 (40 kph)</td>
<td>5.354</td>
<td>5.004</td>
<td>6.401</td>
<td>6.994</td>
</tr>
<tr>
<td>GP16 120 (56 kph)</td>
<td>4.791</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>GP16 120 (80 kph)</td>
<td>4.579</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

$\Delta_{\text{max}}$: maximum deflection (mm).

**Deflection profile along the bridge**

Figures 4 and 5 show the wheel locations and naming convention at which the results were taken for the GP16 and GE80 locomotives, that is, F1-GP16 is when the front wheel of the GP16 locomotive is at a distance 1.90 m from the start of the bridge (at the middle of the first span). Figure 6(a) to (d) illustrates the deflection profile along the bridge for the GP16 locomotive at speeds of 8, 24, 40, 56, and 80 kph. It is evident that the deflection decreases with the increase of the speed and it’s more distinct at higher speeds. For safety reasons and other dynamic effects, this phenomenon is neglected by the AREMA codes. Figure 6(e) shows the deflection profile along the bridge for the GE80 at
a speed of 8 kph for different positions of the front wheel. The maximum deflection is attained when the front wheel is at a distance 12.40 m from the start of the bridge.

**Load profile along the bridge**

The effect of train speed on the load profile of GP16 locomotive is shown in Figure 7(a) to (d). It can be seen that for all the simulated thermoplastic bridges, the ultimate load consistently decreased with the increase of train speed. Also, the difference in stress between bridges with train speed of 8 and 24 kph was significantly larger than the difference between the train speed of 24 and 40 kph, such behavior was expected because large speeds become less effective with the increase of speed rate. Figure 7(e) shows the load profile for GE80 locomotive. Inspection of Figure 7(e) reveals that the lower bound was for the F1 location and the upper bound was for the F5 location.
Stress profile along the bridge

Figure 8(a) to (d) shows the flexural stress profile along the bridge for the GP16 locomotive at speeds of 8, 24, 40, 56, and 80 kph. Negative stress indicates compressive stress. It is observed that the effect of train speed on the flexural stress is not pronounced as in the deflection. Although the trend is toward the decrease of stresses with increase of speed (talk about lumping of speeds). Figure 8(e) and (f) shows the flexural stress profile along the bridge for the GE80 locomotive at speed of 8 kph. Inspection of Figure 8(e) and (f) reveals that the GE80 locomotive had uniform distribution of stresses along the bridge.

Figure 6. Effect of train speed on the deflection profile of thermoplastic bridge.

Stress profile along the bridge

Figure 8(a) to (d) shows the flexural stress profile along the bridge for the GP16 locomotive at speeds of 8, 24, 40, 56, and 80 kph. Negative stress indicates compressive stress. It is observed that the effect of train speed on the flexural stress is not pronounced as in the deflection. Although the trend is toward the decrease of stresses with increase of speed (talk about lumping of speeds). Figure 8(e) and (f) shows the flexural stress profile along the bridge for the GE80 locomotive at speed of 8 kph. Inspection of Figure 8(e) and (f) reveals that the GE80 locomotive had uniform distribution of stresses along the bridge.
Figure 9. Effect of train speed on the load profile of thermoplastic bridge.

Stress profile along the depth

Figure 9 shows the stress profile along the section for F2-GP16 at a speed of 56 kph. Inspection of Figure 9 reveals that the fibers on the upper section are subject to compression stress of 0.883 MPa (negative stress) while the fibers on the lower section are subject to tension of 0.911 MPa (positive stress) for F2-GP16 at a speed of 56 kph. Since there is compression on the top of the section and tension on the bottom, there must be a transition point between the two where there is no stress at all at a distance of 0.2286 m from the top fiber of the section, which is equal to half of the section depth. Therefore,
the stress over the cross section produced force equilibrium in the horizontal direction in which the area under the tension is significantly equal the under compression.

**Effect of train type**

Figure 10 shows the effect of train type on the deflection and flexural stress profile for F2-location at a speed of 8 kph. Inspection of Figure 10 reveals that the GE80 locomotive had feeble impact on deflection and strong impact on flexural stress profile than GP16. The maximum deflection due to GP16 is about 5.51 mm, which is equal to 130% of the deflection of GE80. Also, the area under the deflection profile of the GE80 is equal to...
137% of the area of GP16. Whereas, the maximum flexural stress due to GP16 is about 1.03 MPa, which is equal to 163% of the flexural stress of GE80 and this value is equivalent to 25% of the allowable compressive stress of 4.14 MPa. Finally, the area under the flexural stress profile followed similar general trend as the area under the deflection profile.

**Effect of train speed**

Figure 11 shows the effect of GP16 train speed on the deflection, vertical force, and flexural stress for F3-location. It is obvious from the Figure 11 that the vertical force and displacement decrease with the increase of train speed but the flexural stress decreased
with the increase of train speed up to 40 kph and then flexural stress started to increase slightly with the increase of train speed. Inspection of Figure 11 reveals that the peak deflection for bridge with train speeds of 8, 24, 40, 56, and 80 kph is decreased with percentages of 0%, 3%, 12%, 16%, and 18% with respect to deflection of the train speed of 8 kph, respectively. Also, the peak vertical force followed similar general trend as the peak deflection but with higher percentage reduction of 0%, 5%, 14%, 19%, and 23% with respect to deflection of the train speed of 8 kph, respectively. Also, the results in Figure 11 show that as the minimum flexural stresses occurred at a train speed of 40 kph. Finally, inspection of Figure 11 reveals that the deflection and vertical force versus train speed can be divided into three stages. In the first stage, the vertical force and deflection decreased rapidly up to the train speed of 40 kph followed by a moderate decrease up to overlay train speed of 56 kph, which characterize as second stage. After that, the deflection and vertical force started to decrease slightly as shown in the third stage.

**Effect of material type**

Figure 12 shows the effect of material type on the deflection and flexural stress profile for F2-GP16 at a speed of 40 kph. Inspection of Figure 12 reveals that the wood material
had strong impact on deflection and flexural stress profile than thermoplastic. The maximum deflection due to wood bridge is about 10.11 mm, which is equal to 190% of the deflection of thermoplastic. Also, the area under the deflection profile of the wood bridge is equal to 210% of the area of thermoplastic. On the other hand, the maximum flexural stress due to wood bridge is about 3 MPa, which is equal to 275% of the flexural stress of thermoplastic bridge that reflects the advantage of thermoplastic to sustain more stress and strain before failure. In both cases, the predicted stress levels did not exceed 50% of the allowable stresses. For wood, it’s about 37.5% and 26.5% for the thermoplastic material. Finally, the area under the flexural stress profile followed similar general trend as the area under the deflection profile. Therefore, thermoplastic material is a good alternative because of its performance, environmental, and financial benefits. The following are advantages of using thermoplastic material: thermoplastic is a green solution since it is made of plastic stream lying in landfills and can be recycled after its lifetime, can be molded in any shape to optimize performance since it is a fabricated material, can be effectively used in wet environment with no need to add chemicals and retains its mechanical properties in such environments, can be used in structural application due to its mechanical behavior; and despite thermoplastic’s high initial cost, it pays for it during its expected lifetime of 50 years.

**Conclusions**

Repair and replacement of crossties has been a troubling issue for the people involved in this industry since it is a highly priced process. Moreover, some of the materials used for treatment such as creosote has some toxic properties; in addition to the deforestation polices of wood leading to limited supplies of wood, thus increasing the price of wood. Therefore, thermoplastic (RSPC) was the alternative solution to benefit from plastics stream lying in landfills. The nonlinear finite element model, developed in the present work, predicted vertical load capacity, deflection, and stress in models very well as concluded from comparisons with experimental data.

![Figure 12. Effect of material type on the deflection and flexural stress profile for F3-GP16 at 40 kph.](image-url)
The GP16 had a strong impact on deflection and strong impact on flexural stress profile than GE80. The increasing of train speed decreased the flexural stresses, vertical force capacity, and deflection, which indicate a considerable decrease in the structural ductility. The wood material had the strongest impact on the characteristic of bridge behavior, which had the highest flexural stress and the deflection. However, the thermoplastic material had an excellent impact on deflection, which offered a strong and ductile structure. Based on this study thermoplastic material can be considered as a good alternative because of its performance in terms of stress, vertical force, and corresponding deflection.

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