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Vibration Analysis of Thermoplastic Railroad Bridge

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ABSTRACT

Thermoplastic materials are used as a feasible green solution and as an alternative to wood in railroad bridges. A vibration analysis is conducted on a four-span rail road bridge to evaluate the behavior of thermoplastic *versus* wood materials, using the finite element analysis to determine the free undamped natural frequencies and mode shapes. Also, natural frequencies and mode shapes under GP 16-120 ton locomotive were extracted. The models studied the effect of material type (thermoplastic and wood) on the natural frequencies and mode shapes for the loaded cases. It is clearly shown that thermoplastic materials have higher natural frequency values than wood. Based on the results of this study, thermoplastic materials can be considered as a good replacement to wood.

KEYWORDS: Vibration, Natural frequency, Mode shapes, Finite element analysis, Thermoplastic, Railroad bridge, Wood.

INTRODUCTION

The cost of maintaining current steel, timber and reinforced concrete bridges due to environmental factors, such as corrosion and bio-degradation, has escalated. The cost is estimated to be in the neighborhood of $300 billion dollars per year (Jackson and Nosker, 2009). About 10 to 15 million wood railroad cross-ties are replaced annually due to their poor performance in wet environment (Lynch et al., 2002). The price of wood is on the rise due to laws and policies that protect trees and forests (Nosker et al., 1996). The need for new materials as an alternative to existing conventional materials, such as steel, concrete and wood, has become a necessity. These new materials should be more durable, sustainable and environmentally friendly. A new material is enhanced reinforced structural plastic composite (RSPC, also known as thermoplastic). RSPC is an immiscible polymer blend (IMPB) with reinforcing agents, such as polypropylene (PP)-or polystyrene (PS)-coated glassed fiber, merged within the recycled plastic lumber (RPL) matrix. RSPC does not require any maintenance (corrosion, insect and rot resistant) for at least 50 years (Lynch et al., 2002). RSPC does not seep toxin chemicals into soil or water. Moreover, it lessens deforestation and greenhouse gases. It is recyclable and possesses the capability of absorbing high energy (Lampo et al., 2011; Nosker et al., 2012). The Facility for Accelerated Service Testing Track at the American Association of Railroad and Transportation Technology Center in Pueblo, Colorado, installed a total of 48 plastic/composite cross-ties. The cross-ties were subjected to 182 million gross tons and showed no deterioration after inspection (Nosker et al., 1999). The

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first plastic lumber civil structure of major significance was constructed by New York City Department of General Devices at the Tiffany Street pier located in the Bronx in New York City (Lampo, 2004). The first thermoplastic vehicular bridge (twenty-four foot span bridge) was built by the United States Army at Fort Leonard, Missouri, with maximum load capacity of 29,430 kg. Inspection of the bridge after thirteen years showed no signs of degeneration and required no maintenance (Nosker and Lampo, 1996). In 2010, the United States Army commissioned the replacement of two railroad timber bridges at Fort Eustis, Virginia. All the components of both new bridges were made of thermoplastic materials except for the existing abutments. The first bridge (Bridge No.3) comprises four spans with a total length of 11.44 m. The second bridge (Bridge No.7) is 25.6 m long and consists of eight spans (Kim et al., 2010). In 2015, Diaz-Alvarez et al. conducted a finite element analysis on a thermoplastic composite bridge located on Tuckers Road in North Carolina. The bridge was made with 94% recycled high-density polyethylene. The analysis proved that the bridge exceeded design specifications. Karbhari et al. (2015) developed an ultimate strength design procedure for thermoplastic beams. Al-Rousan et al. (2016) performed a non-linear finite element analysis on thermoplastic bridges to determine 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. This study is an extension to their work by studying the vibration adequacy of thermoplastic bridges in terms of natural frequencies and mode shapes in comparison to wood bridges.

FINITE ELEMENT ANALYSIS

10 models were simulated using the finite element software ABAQUS (2010). Free natural undamped frequencies and mode shapes were extracted for both thermoplastic and wood bridges. The GP 16 120 ton (117000 kg) (GP16) locomotive is used to extract the loaded natural frequencies and mode shapes for both materials. The model was validated in Al-Rousan et al. (2016). The bridge cross-section used in the models is shown in Figure 1. The length of the bridge is 11.44 m (Kim et al., 2010). The mechanical properties of the thermoplastic material used in the models are listed in Table 1 (Lampo et al., 2003). Figure 2 shows the stress-strain relationship, stress relaxation data and normalized shear modulus *versus* time. The normalized shear modulus is implemented through the use of Prony series in ABAQUS (ABAQUS, 2010). The instantaneous modulus G_0 and bulk modulus K_0 are found from the modulus of elasticity and Poisson's ratio given in Table 1 (Lampo et al., 2003).

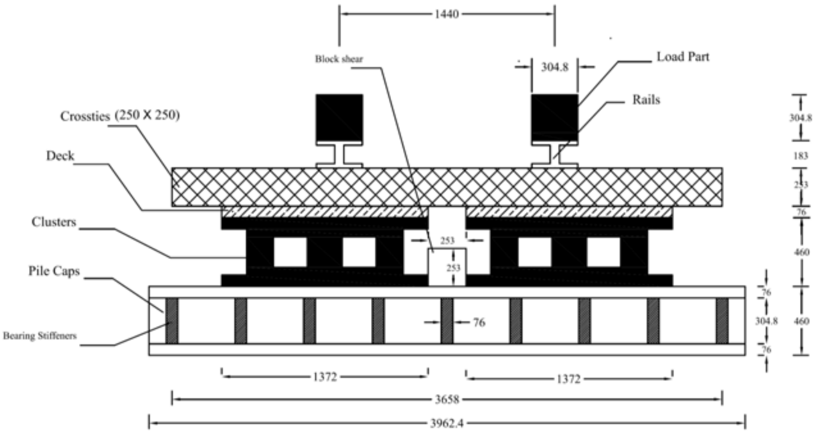


Figure (1): Bridge cross-section. All dimensions are in mm

Table 1. Mechanical properties of thermoplastic material

Specific Gravity (ASTM D6111)	0.85-0.90
Elastic Modulus (ASTM D6108)	2413.2 MPa
Allowable Tensile Stress (ASTM D638)	4.14 MPa (Ultimate = 20.68 MPa)
Allowable Flexural Stress (ASTM D6109)	4.14 MPa (Ultimate = 17.24MPa)
Allowable Compressive Stress (ASTM D695)	4.14MPa (Ultimate =17.24 - 29.6 MPa)
Allowable Shear Stress (ASTM D6109)	2.41 MPa (Ultimate = 10.34 MPa)
Coefficient of Thermal Expansion (ASTM D696)	0.0000508 m/m/deg C
Density	881 kg/m^3
Poisson’s Ratio	0.35

The shear long-term modulus was assumed to be the one at the end of the shear modulus curve at time equal to 2160 hrs. The mechanical properties of the wood (white oak) used in the models are listed in Table 2 (Yu and David, 2012). Making use of the symmetry along the longitudinal direction (z-axis), only one half of the bridge was modeled. The GP16 used in this model is classified as a B-B type wheel arrangement locomotive with 4 wheels on each side with a diameter of 1.0 m and the distance between the wheels (center to center) is 2.74 m. Distance between the centers of the last wheel and the first wheel is 6.71 m (Al-Rousan et al., 2016).

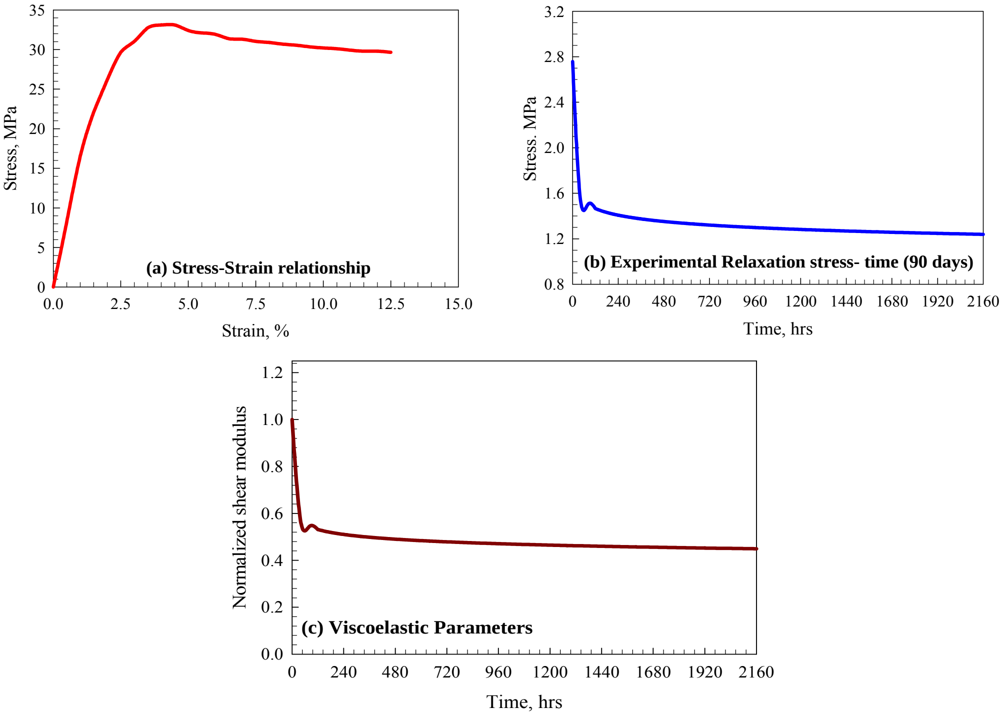
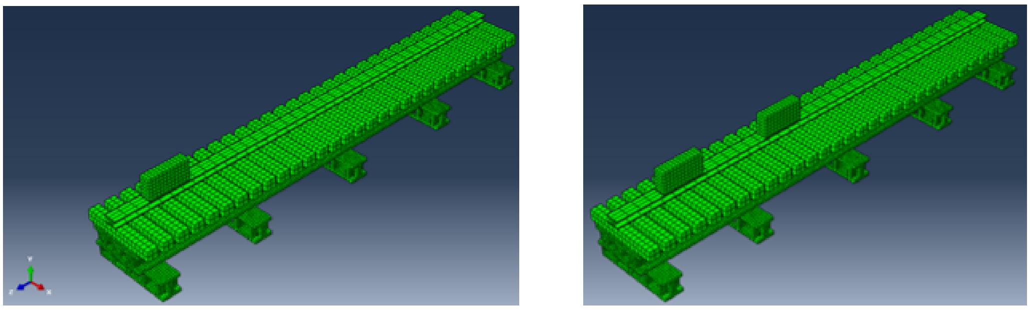


Figure (2): Thermoplastic material stress-strain relationship, stress relaxation data and normalized shear modulus *versus* time (Lynch et al., 2002)

The locomotive loads were modeled as 2 blocks that simulate the wheels of the train. The dimensions of the block are as follows: 1.0 m in length and 0.5 m in height with a width equal to 0.30 m. The total length of the GP16 is 17 m (longer than the bridge), thus only two wheels were needed to model the loaded cases as shown in Figure 3. The element type selected for the analysis was an eight-node linear brick incompatible mode element to reduce the development of any artificial energy (designated in ABAQUS as C3D8I (ABAQUS 2010)).

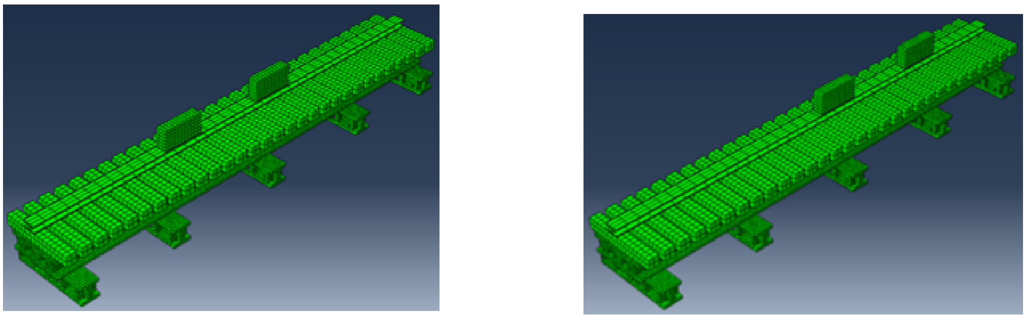
Table 2. Mechanical properties of wood

Constant	**Value**			
Elastic Modulus	E_1	13500 MPa		
	E_2	2200 MPa		
	E_3	972 MPa		
Shear Modulus	G_{12}	1161 MPa		
	G_{13}	1094 MPa		
	G_{23}	284 MPa		
Possion's Ratio	υ_{12}	0.369	υ_{21}	0.0601
	υ_{13}	0.428	υ_{31}	0.031
	υ_{23}	0.618	υ_{32}	0.273



Front Wheel located in 1st span

Front Wheel located in 2nd span



Front Wheel located in 3rd span

Front Wheel located in 4th span

Figure (3): Location of the wheels of the GP16 locomotive

RESULTS AND DISCUSSION

Effective Mass

To determine the number of modes and frequencies to be extracted, use is made of the effective mass (EM) for each mode. A mode with a large effective mass in any direction is considered as a significant contributor to the response of the system. The sum of the effective mass of all modes in any direction must be equal to the total mass in that direction (x, y or z). The ratio of the summation of the effective mass of chosen modes to the total mass should be more than 90% (Priestley et al., 1996). Figures 4 through 6 show EM *versus* mode number for the unloaded thermoplastic and wood bridge. The first 30 modes are adequate in the transverse (y) direction for both the thermoplastic material and wood material, while 20 modes are adequate for the longitudinal direction (z-direction). For the lateral (x) direction, the first 40 modes are adequate for the thermoplastic material, while the higher modes (40 to 79) are required for the wood material. The loaded cases showed similar behavior.

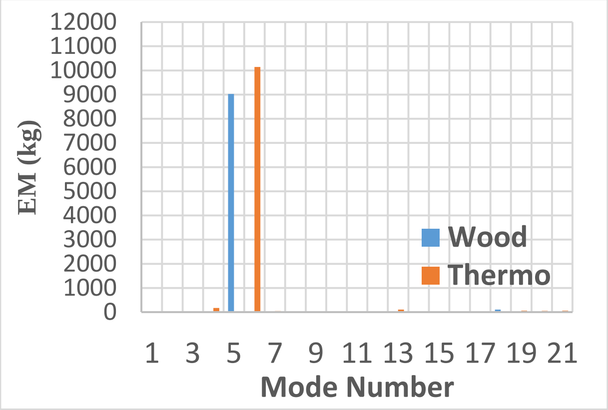


Figure (4): Effective mass *versus* mode number in the longitudinal direction

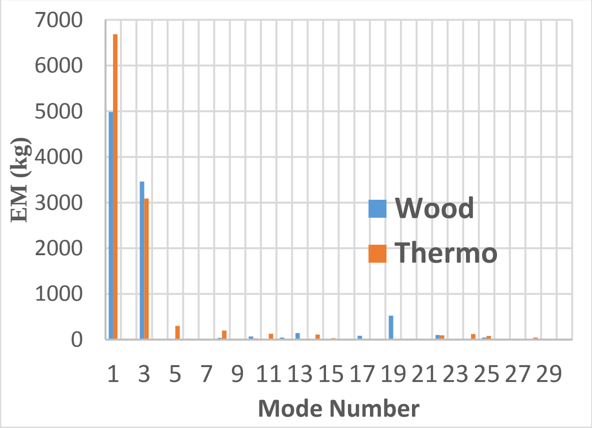


Figure (5): Effective mass *versus* mode number in the transverse direction

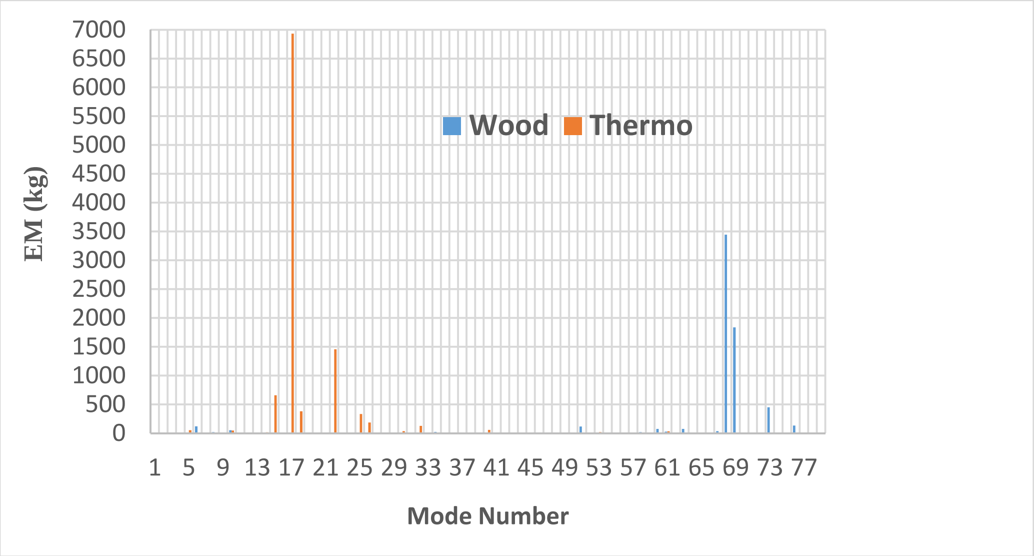


Figure (6): Effective mass *versus* mode number in the lateral direction

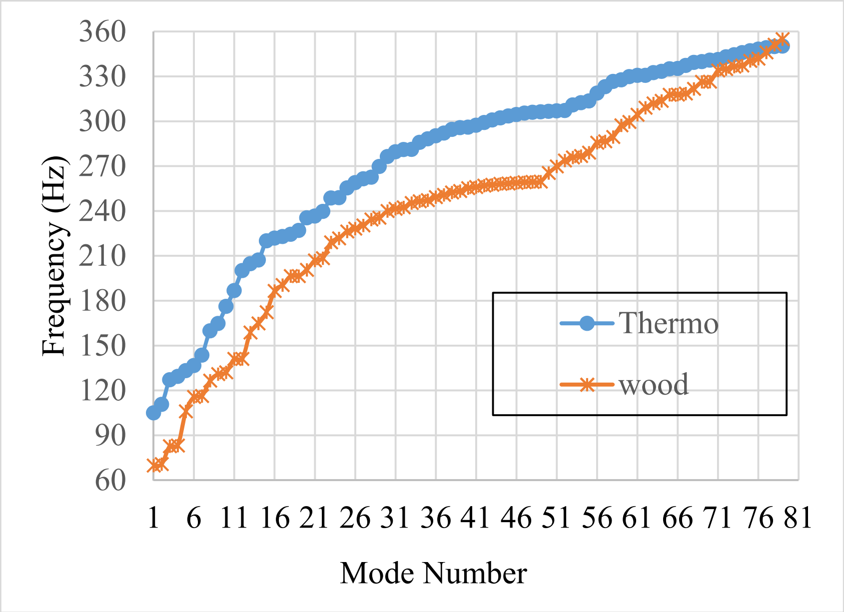


Figure (7): Frequency *versus* mode number for unloaded thermoplastic and wood bridges

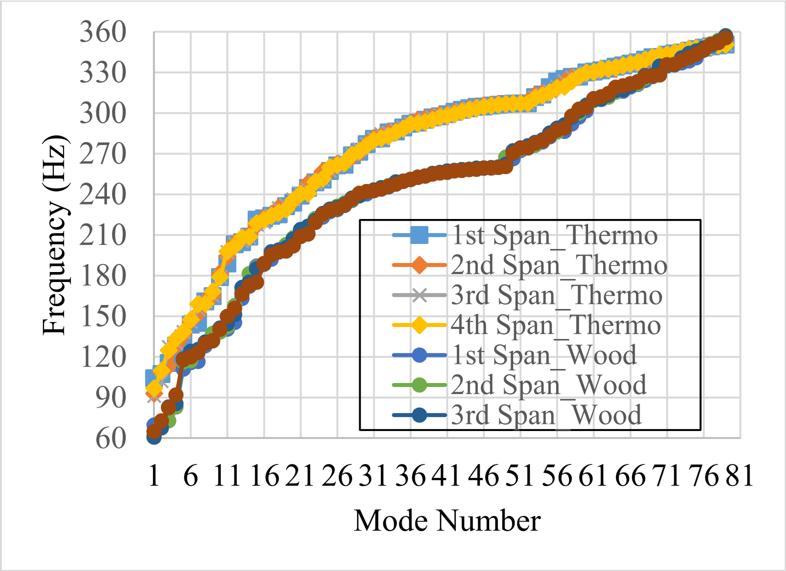
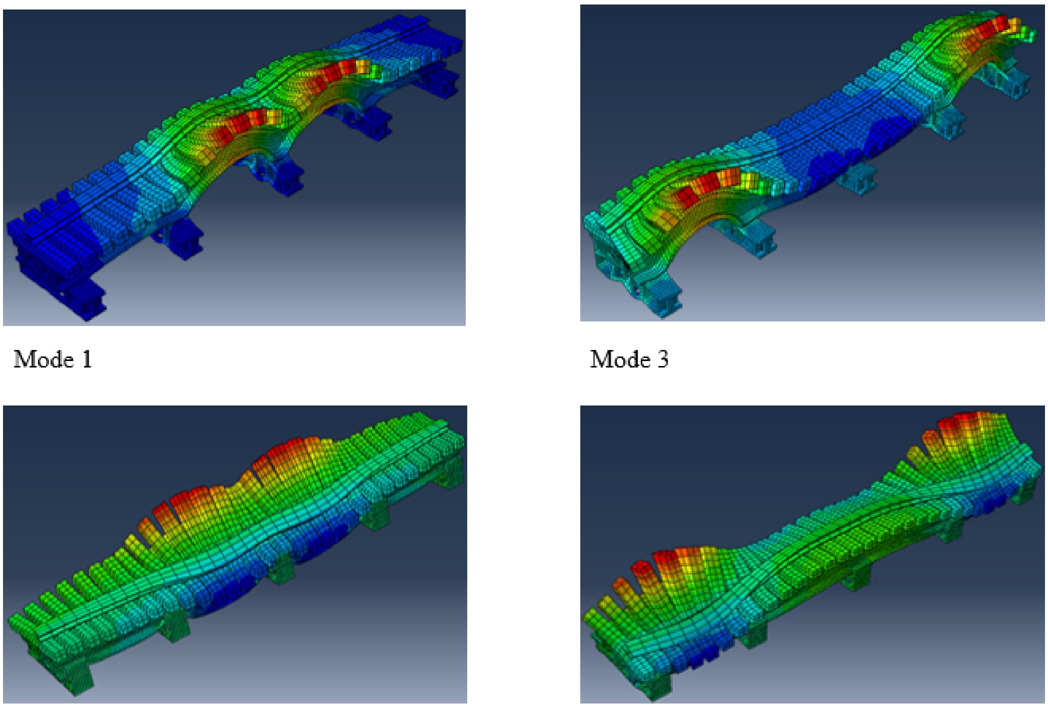


Figure (8): Frequency *versus* mode number for the loaded thermoplastic and wood bridges


Mode 1 Mode 3

Mode 5 Mode 8

Figure (9): Mode shapes for the unloaded thermoplastic bridge in the transverse direction

Frequency Extraction and Mode Shapes

The extracted frequencies of vibration are shown in Figures 7 and 8. From Figure 7, the first 4 modes of the frequency of vibration for the thermoplastic bridge are (105, 110, 127 and 129 Hz) and for the wood bridge (69, 70, 82 and 83 Hz). Thus, the frequencies of vibration values for the thermoplastic bridge are 50% higher on average than those for the wood bridge for the first 4 modes and 20% higher on average for the rest of the modes up to mode 60. For the loaded case of first wheel located in the first span (FW1), there is an increase in the frequency values for modes 1, 2 and 3 (5% on average) when compared to the unloaded case. For the higher modes, a decrease (between 1% and 3%) in values of the frequencies of vibration is observed irrespective of material type. As for when the first wheel is located in the second span (FW2), the same observation is made, but with higher percentages (increase is 10% on average, whereas decrease is between 2% and 9%). For the remaining load cases (load in the third span (FW3) and in the fourth span (FW4)), the increase is only in the first two modes for the thermoplastic material and the first mode for the wood material. The typical mode shapes for the unloaded case are shown in Figure 9.

CONCLUSIONS

The vibration analysis performed in this study compares the natural frequency of vibration and mode shape for wood and thermoplastic four-span bridges. In the longitudinal direction, only the lowest 20 modes are required for modal analysis for both materials. Also, only the lowest 30 modes are required for modal analysis in the transverse direction for both materials. As for the lateral direction, the modes required are the lowest 40 modes for thermoplastic material, while for wood the higher modes (40 to 79) are required. The frequencies of vibration values for the thermoplastic material are higher than those for the wood material, which is considered as an advantage, since it reduces the risk of resonance. Thus, for the thermoplastic and wood materials considered in this study, thermoplastic material can be considered as a good replacement.

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