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Dynamic Behaviors of Precast Steel-Concrete Composite Railway Track Slabs

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ABSTRACT:

This paper highlights an investigation into the dynamic behaviours of a precast steel-concrete composite slab panel for railway track slabs. The steel-concrete composite slab track is an evolvement from the slab track, a form of ballastless track which is becoming increasingly attractive to asset owners (over the conventional ballasted track) as they seek to reduce lifecycle costs and deal with increasing rail traffic speeds. The precast steel-concrete composite slab track is much suited for the replacement of existing track and transom elements on existing steel girder railway bridges due to its savings in depth of construction, self weight and ease of construction. The slender nature of the slab panel due to its reduced depth of construction makes it susceptible to vibration problems. The goal of the study is to successfully address the dynamic behaviours of steel-concrete composite slab panels in three dimensions. A finite element model has been established and validated using ABAQUS/Standard. Lancsoz method has been used to identify natural frequencies and corresponding mode shapes. The first 15 natural frequencies and associated natural modes of vibration of the slab panel were identified. Effect of alternative materials in lieu of the steel sheeting has also been investigated and highlighted in this paper. Our studies show that the damping had marginal effect on the dynamic behaviours of the track slab panel.

Keywords: steel-concrete composite slab, natural frequencies, natural nodes, eigenfrequency, eigenmodes

1. INTRODUCTION

Steel-concrete composite slab panel for track support is currently being considered in the replacement of ageing deck elements in steel-girder railway bridges. Growing economic pressures in addition to the increase in train speeds and axle loads are making a ballast track less favourable and less attractive as compared to a ballastless track. This is pushing railway asset owners to reduce their life cycle costs by adopting ballastless track systems (Robertson et al. 2015).

However, although the steel-concrete composite slab panel offers a reduction in dead load and improved durability (Griffin et al 2014, 2015), it's slender nature due to its reduced depth makes it more susceptible to vibration problems (De Silva and Thambiratnam 2011). Based on the literature review carried out for this study, it was identified that there is limited information on the vibration behavior of the steel-concrete composite slab panels for track support. A study was hence conducted aimed at bridging this gap and provide new findings to improve railway vibration control methods. The understanding of natural frequencies can enable improved designs to cater for high frequency vibrations from trains. This paper focuses on the study carried out on free and damped vibrations of a steel-concrete slab track panel model developed by (Griffin 2003) for the finite element analysis of derailment loading.

2. FINITE ELEMENT MODEL

In depth details of how the model of the steel-concrete composite slab used in the study was developed can be found in (Griffin 2013). Figure 1 shows the model adopted. In order to suit this study some amendments were made to the model, which included assignment of mass properties to the constituent materials in the composite slab model as well as variation of strength, stiffness and mass properties in the composite slab panel for the parametric study.

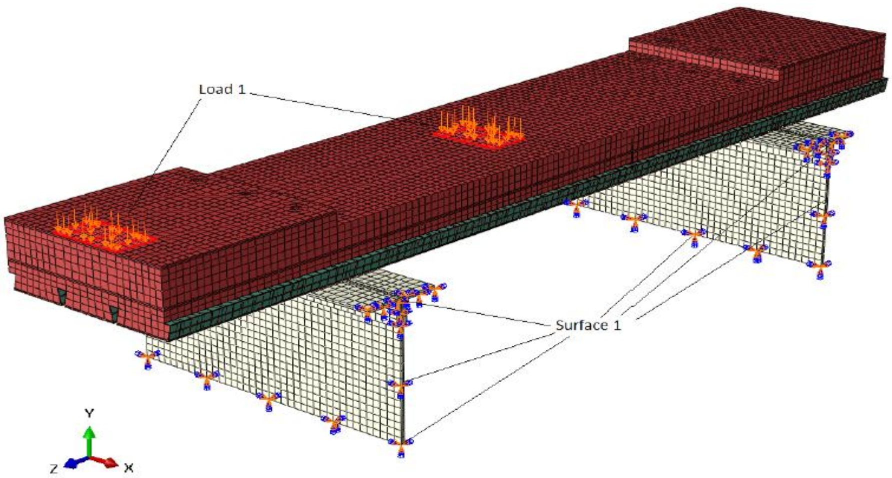


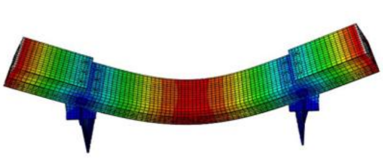
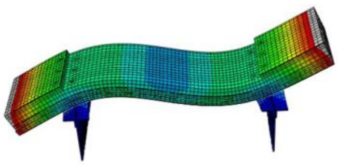
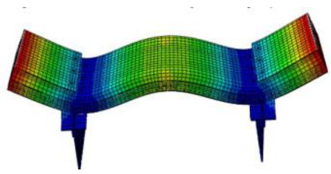
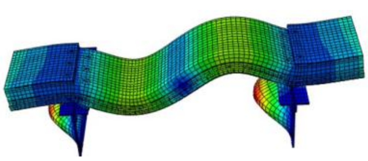
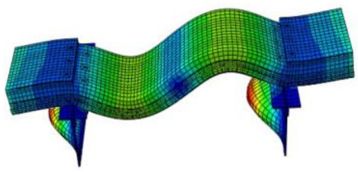
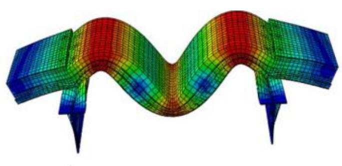
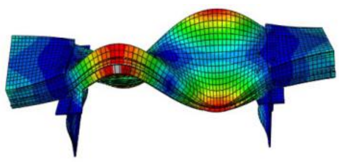
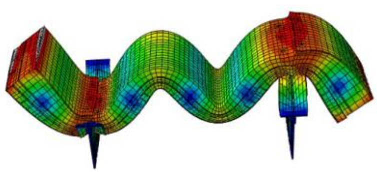
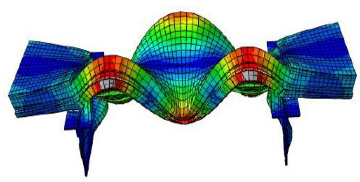
Figure 2: FE model adopted from (Griffin 2013)

3. FREE VIBRATION ANALYSIS

3.1 Natural frequencies and mode shapes

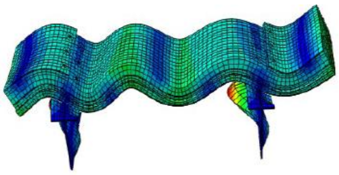
The Lanczos method was adopted for the eigenvalue extraction in ABAQUS/Standard. The Lanczos eigensolver was used to extract the first 500 eigenfrequencies and eigenmodes of the slab panel. Of the 500 eigenfrequencies, only 15 distinctive mode shapes were identified as the natural modes of vibration which meant that only the first 15 natural modes of vibration were considered and these are presented in Table 1 below.

Table 1: Modes of vibration, natural frequency (Hz) and corresponding mode shapes

1st Mode - Transverse bending, 2.5981 Hz 	2nd Mode - Transverse bending, 4.1649 Hz 	3rd Mode - Transverse bending, 6.880 Hz 
4th mode – Torsion, 9.7121 Hz 	5th mode - Transverse bending, 12.3709 Hz 	6th mode – Transverse bending, 20.8487 Hz 
7th mode – Torsion, 21.1339 Hz 	8th mode – Transverse bending, 27.1507 Hz 	9th mode – Torsion, 32.3012 Hz 

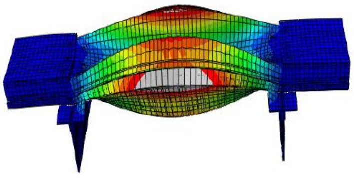
10th mode – Torsion

37.1369 Hz



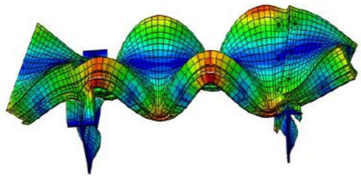
11th mode – Bi-directional Bending

38.8362 Hz



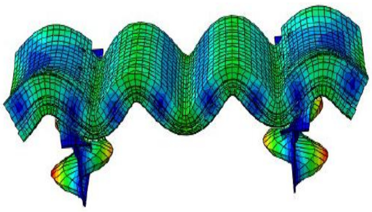
12th mode – Torsion

42.3631 Hz



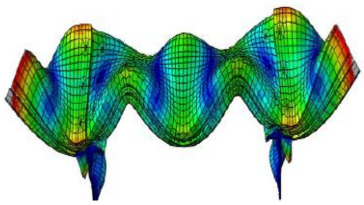
13th mode – Transverse bending,

46.0272 Hz



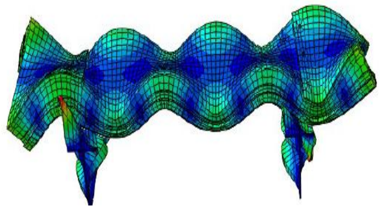
14th mode – Torsion,

46.7509 Hz



15th mode – Torsion,

51.2766 Hz



3.2 Effect of alternative deck sheeting materials

As an alternative to steel sheeting, aluminum and high modulus carbon fibre (HMCF) were used. Table 2 below shows the arbitrary properties of both aluminium and HMCF used (Tindall 2008 and ACP Composites 2016) together with those adopted for profiled steel sheeting. It is worth noting that the mass and stiffness values of aluminium and HMCF for the study were arbitrarily chosen as the study was undertaken with the sole purpose of illustrating the sensitivity of the vibration behavior of the slab panel to mass and stiffness of concrete and steel.

Table 2: Steel, aluminium and HMCF material properties used in the study

Material	Profiled steel sheeting	Aluminium	High Modulus Carbon Fibre (HMCF)
Properties	Yield stress: 550N/mm^2 Thickness: 1.0mm Modulus of Elasticity: 200000N/mm^2 Poison ratio: 0.3	Yield stress: 290N/mm^2 Modulus of elasticity: 78500N/mm^2 Poison ratio: 0.325 Mass: 2750Kg/m^3	Yield stress (tensile/compressive): 350/150N/mm^2 Modulus of elasticity (0 °and 90 °): 85000N/mm^2 Poison ratio: 0.1, Mass: 1600Kg/m^3

Figure 2 below shows the comparison of natural frequencies obtained when steel, aluminium and carbon sheeting are used.

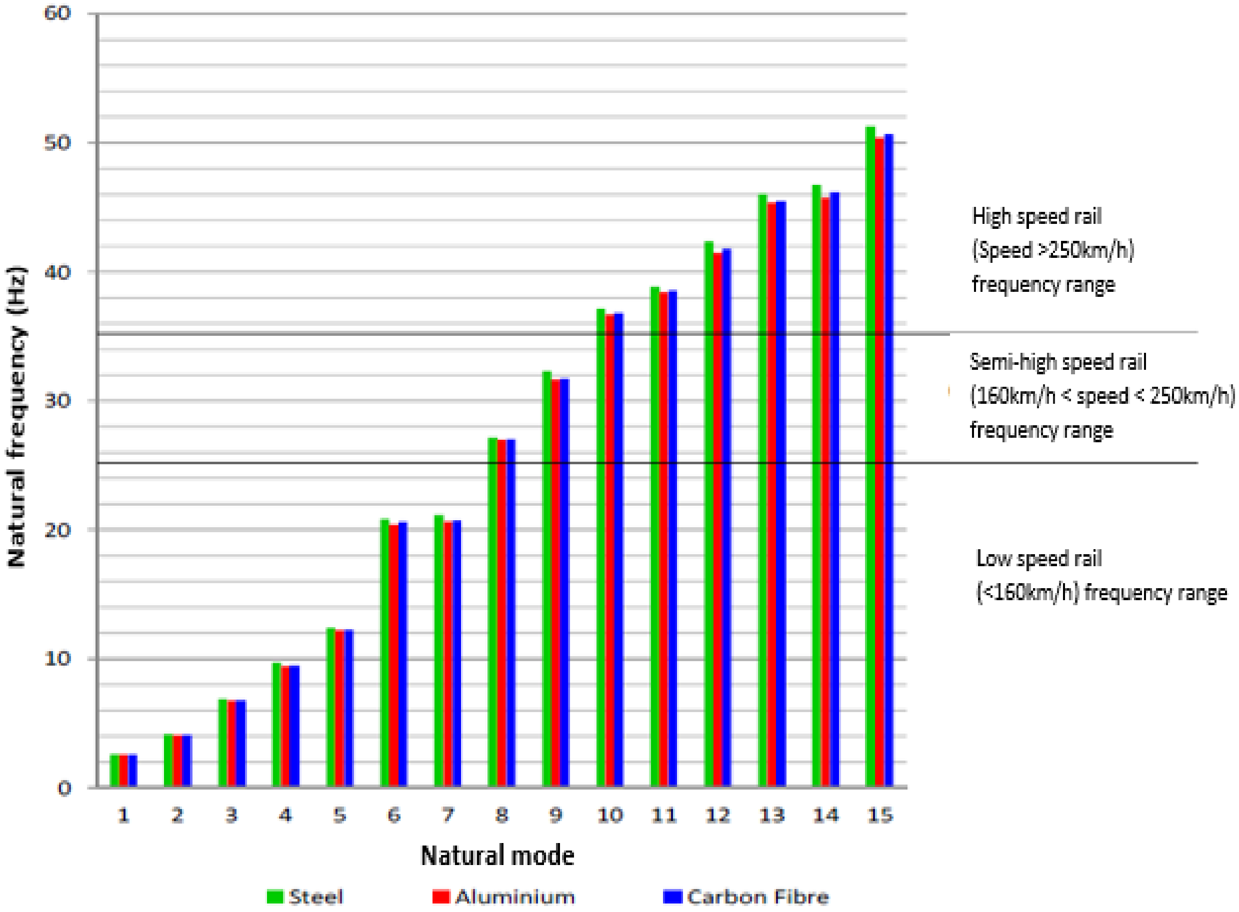


Figure 2: Natural frequencies of slab panel with steel, aluminium and carbon sheeting and the correlation of the natural frequencies with typical rail frequency ranges

4. DAMPED SYSTEM NATURAL FREQUENCIES

ABAQUS/Standard was used to compute composite damping ratios for the natural modes of the slab panel based on material damping ratios of 1% for steel and 2% for concrete (Feldmann et al 2009). For each of these composite damping ratios, the corresponding damped natural frequencies are presented in table 3 below. Table 3 also presents the damped natural frequencies associated with uniform damping ratios of 1%, 2%, 3%, 4% and 5%.

Table 3: Damped natural frequencies of slab panel at various damping ratios

Mode of vibration			**Material Damping Ratio**				
	ABAQUS/Standard computed composite damping ratio (%)	Frequency due to composite damping ratio (Hz)	Uniform damping ratio and corresponding natural frequencies				
			1%	2%	3%	4%	5%
1st mode	1.9011	2.5976	2.5979	2.5976	2.5969	2.5960	2.5948
2nd mode	1.9145	4.1642	4.1647	4.1641	4.1631	4.1616	4.1597
3rd mode	1.9099	6.8787	6.8796	6.8786	6.8769	6.8745	6.8714
4th mode	1.8989	9.7104	9.7117	9.7102	9.7078	9.7044	9.7000
5th mode	1.7896	12.3689	12.3703	12.3684	12.3653	12.3610	12.3554
6th mode	1.8355	20.8452	20.8477	20.8445	20.8393	20.8320	20.8226
7th mode	1.8821	21.1302	21.1328	21.1297	21.1244	21.1170	21.1075
8th mode	1.8094	27.1463	27.1493	27.1453	27.1385	27.1290	27.1167
9th mode	1.8483	32.2957	32.2996	32.2947	32.2867	32.2753	32.2608
10th mode	1.7671	37.1311	37.1350	37.1295	37.1202	37.1072	37.0904
11th mode	1.8828	38.8293	38.8343	38.8284	38.8187	38.8051	38.7876
12th mode	1.8135	42.3561	42.3610	42.3546	42.3440	42.3292	42.3101
13th mode	1.6600	46.0209	46.0249	46.0180	46.0065	45.9904	45.9696
14th mode	1.8421	46.7430	46.7486	46.7415	46.7299	46.7135	46.6924
15th mode	1.7422	51.2688	51.2740	51.2663	51.2535	51.2356	51.2125

The study found that the effect of the variation of the uniform damping ratio on the natural frequencies of the slab panel was polynomial, based on equation 1 below (Chopra 2011).

$$f_{nD} = f_n\sqrt{1-\xi_n^2} \quad (1)$$

Where f_{nD} is the damped natural frequency, f_n is the undamped natural frequency and ξ_n is the damping ratio.

Based on the above equation, the percentage decrease in the natural frequency for 1% to 5% uniform damping ratios is shown on table 4 below.

Table 4: Percentage decrease in natural frequency for uniform damping ratios 1% to 5%

	Uniform damping ratio				
	1%	2%	3%	4%	5%
Percentage decrease in natural frequency	0.005%	0.020%	0.045%	0.080%	0.125%

5. CONCLUSIONS

The fundamental natural mode shape was identified as transverse bending of the slab panel. A correlation of the natural frequencies of the slab panel with typical rail traffic frequency ranges showed that resonance damage from rail traffic vibration would likely result from transverse bending for low speed rail traffic, whilst this type of damage would likely result from both transverse bending and torsion for mid-high speed and high speed rail traffic. The fundamental undamped natural frequency of the slab panel was found to be 2.5981Hz whilst the fundamental damped natural frequency was determined as 2.5976Hz for a composite damping ratio of 1.9011%

Use of alternative deck sheeting materials (aluminium and carbon fibre sheeting) had the effect of lowering the fundamental natural frequency of the slab panel, however the differences were marginal among the three materials which led us to the conclusion that replacing the steel sheeting with aluminium or carbon fibre would have little effect on the dynamic behaviour of the slab panel. By varying the uniform damping ratio of the slab panel, it was found that the natural frequency decreased at a polynomial rate as the damping ratio increased.

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