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“Dynamic mode couplings of railway composite track slabs”

(Title contains 49 characters)

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Dynamic mode couplings of railway composite track slabs

Sakdirat Kaewunruen[1] **and Stephen Kimindiri Kimani**

Abstract: Steel-concrete composite railway track slabs are a financial-viable alternative for the modular construction of railway slab tracks and for the replacement of resilient timber transoms on railway bridges. The design and experiment had been carried out to investigate the technical feasibility. In this study, the extended outcomes based on dynamic eigenvalue analyses of precast steel-concrete composite slab panel for track support structure are presented. Using ABAQUS finite element package, the natural frequencies of the railway composite slabs can be investigated. Dynamic eigenmodes are then extracted using Lancsoz method. Modal crossover phenomena can be clearly observed when changing the design mass of track slabs. This paper highlights the unprecedented dynamic mode coupling effects on the composite track slabs over a railway bridge in which the insight can improve practical noise and vibration control technologies through composite material design resulting in quieter railway track slabs.

Keywords: railway infrastructure, modular track slabs, resilient precast composites, dynamic design.

ICE Keywords: railway systems, rail track design, railway tracks, infrastructure planning,

1. Introduction

Railway track components are principally designed to interact in order to transfer the imposed dynamic loads from the wheels of the railway vehicle to the foundation or support structure of the track as well as to secure safe passage of trains (Remennikov and Kaewunruen, 2008; 2014; Remennikov et al., 2012). These dynamic loads include both vertical loads influenced by the unsprung mass of the vehicles and lateral loads mobilized by centrifugal action of cornering or the momentum of breaking vehicles (Griffin et al., 2014; 2015). There are two dominant trackforms including ballasted and ballastless tracks. Bonnett (2005) defined ‘ballasted tracks’ as incorporating an intermediate layer known as the ‘trackbed’ comprising ballast and sub-ballast (or called ‘capping layer’ in Australia) to effectively distribute the vehicle loads to the compacted soil layer called ‘sub-grade’

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(Indraratna et al., 2011). If the intermediate load distribution layer is replaced by a structure directly sit on the sub-grade or the superstructure of a bridge or tunnel, it is known as a non-ballasted track system. Based on the current design approach, the design life span of structural concrete components is around 50 years (Mirza et al., 2016; Standard Australia, 2003). Modern railway tracks have adopted track slab systems to enable low-maintenance regime. For example, there has been an attempt to convert such transom bridges into direct-fixation track slab bridge. Common uses of track slabs can also be observed in tunnelling systems (e.g. Crossrail in the UK) and in highspeed rail track systems (e.g. Shinkansen in Japan). The design methodology and procedure for track slabs generally yields heavy concrete slabs with a thickness of over 220mm. As a result, the vertical levels (or heights) of adjacent systems such as fastening systems, rails, overhead wires, platforms and existing bridge girders must comply with such track slabs (Kaewunruen and Remennikov, 2008; 2010; Kaewunruen, 2014a,b; Li et al., 2012; 2014). Technical feasibility evaluations using numerical and experimental studies of composite track slabs have been carried out under static and dynamic loading conditions (Mirza et al., 2016; British Standards Institution, 1994; 1995). However, the dynamic behaviour of composite composite track slabs has not been thoroughly carried out. The understanding into dynamic behaviours is imperative to predict pre-mature failure modes under dynamic loading condition. The insight can also help track engineers to prioritise the area of inspection for structural track components. In addition, it can help track and acoustic engineers to formulate vibration control techniques that can effectively suppress either structural- or ground-bourne vibration along railway corridor. Without appropriate acoustic and vibration controls, track problems can incur (Kaewunruen and Remennikov, 2016). As a result, this paper highlights the extended study into the unparalleled dynamic behaviour of composite composite track slabs using ABAQUS. The natural frequencies and dynamic eigenmodes of the railway composite slabs are then investigated. It is important to note that the scope of this study is limited to railway viaduct since a railway viaduct more often emits nuisance noise radiation (structural bourne noise). On-ground railway track will form a future study. The outcome of this study will help asset designers and maintainers to establish an improved noise and vibration mitigation methodology for safer and quieter railway bridge systems.

2. Finite Element Modelling

The composite track slabs have been designed, validated and evaluated using numerical and experimental studies in the past (Griffin et al., 2014, 2015; Kaewunruen et al., 2015, 2016;

Mirza et al., 2016). The structural design was in accordance with AS5100 (Standards Australia, 2004). Based on the serviceability limit state, the slab should not resonate with load frequency spectra. This could be confirmed by the numerical modelling. In this study, solid, three-dimensional, eight node elements incorporating linear approximation of displacements, reduced integration and hourglass control (C3D8R) have been adopted in this extended study to model all of the parts with the exception of the steel reinforcing. The C3D8R element type has been found to be sufficient for linear and nonlinear models, and is capable of incorporating contact properties, handling large deformations and accommodating plasticity. The use of C3D8R elements increases the rate of convergence of the solutions (Mirza et al., 2010; 2011). C3D8R elements were similarly adopted by Lam and El-Lobody (2001) for modelling the general concrete and steel beams for push tests, however 15 and 20 node elements were adopted for the concrete around the shear studs and the shear studs respectively. Eight node elements have been determined to provide sufficient accuracy for the models within this study as shown in Figure 1. The composite track slab is hinged by full-scale bridge girders (I-beam) and modelled using surface contacts as a continuous support (Kimani and Kaewunruen, 2017). The full-scale fastening system has been modelled using collogn-egg design (Kaewunruen and Kimani, 2017). However, the influences of elastomeric pads are outside the scope of this paper. The experimental validation details are presented in Mirza et al. (2016). Material properties are tabulated in Table 1.

3. Natural Frequencies

The eigenfrequencies and corresponding eigenmodes extracted by the Lanczos eigensolver from the free vibration analysis have been identified and associated with distinctive natural mode shapes that could be excited by train loading conditions. These natural frequencies of the composite slab panel and their associated mode shapes are tabulated in Table 2. Figure 2 displays these corresponding mode shapes. The operational loading condition under normal train passages suggests that the lower range of frequency between 0 and 25 Hz can be induced by low speed train operations (such as trams, light rails, construction machines, etc.). In addition, the frequency range from 25 and 35 Hz can be induced by faster trains (e.g. suburban rails, intercity trains, etc.); and higher range from 35 to 50 Hz can be associated with the loading condition from high speed trains. As a result, the information in Table 2 and Figure 2 indicates practical dynamic loading ranges that the composite slab can respond to. In addition, it can be observed that torsional modes have become a significant behaviour of the slab since the aspect ratio of the slab (width over depth) can result in additional torque and torsional failure mode. Especially when there is an irregularity on either wheel or rail, the dynamic train-track interaction can induce torsion (or track twist) and cause torsional vibrations and damage on the track support slabs (Malveiro et al., 2014; 2018a; 2018b; Montenegro et al., 2015; 2016). It is thus important to note such the dynamic mode coupling when any vibration control techniques are designed (Chopa, 2017; Kaewunruen et al., 2018).

4. Modal Crossovers

In most practical cases, the design of track slab is restrained by physical supporting infrastructure. Constraint on the dead load (weight) of the slabs is often imposed as a concern of rail engineers and practitioners. Often, the material design has been modified to adopt other type of cement-based composites such as foamed concrete, light-weight concrete, fibre-reinforced foamed concrete, recycled aggregate concrete, etc. The use of these materials can indeed changes the dynamic phenomena of the composite track slabs as illustrated in Figure 3. It is found that modal crossover can be observed in two dominant frequency ranges: firstly, between 20 and 24 Hz; and secondly, between 45 and 55 Hz. These phenomena imply that the composite slab can change the modes of vibration and the noise and vibration control strategies may not be effective when modal crossovers occur. Especially at higher frequency, torsional mode can incur in coupling with transverse bending modes, resulting in premature asset failures (e.g. fastening system loosening, broken bolts and fixture, etc.). This insight is thus vital for rail track engineers in order to design and control the behaviours of track slabs and develop predictive maintenance strategies (Lam et al., 2015; Li and Conte, 2016).

5. Concluding Remarks

Global demand of a trackform alternative for railway construction and maintenance is significant, especially for steel-concrete composite track slabs. This paper presents unmatched dynamic phenomena of the composite track slabs within railway built environment. The use of composites in railway construction and maintenance require comprehensive considerations and systems thinking approach. This paper has demonstrates practical design issues and dynamic requirements associated with the design of the composites that can enable quieter railway track slabs. It is crucial to understand the modal crossovers in order to establish effective noise and vibration control methodology.

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Table 1: Precast steel-concrete composite slab panel materials properties

Material	Properties
Concrete	28 days cube strength, f'c: 50N/mm^2
	Short-term modulus of elasticity: 34652N/mm^2
	Poison ratio: 0.2
	Mass: 2400Kg/m^3
Profiled steel sheeting (High Tensile Steel Bondek II profile manufactured by BHP Building Products)	Yield stress: 550N/mm^2
	Thickness: 1.0mm
	Modulus of Elasticity: 200000N/mm^2
	Poison ratio: 0.3
Tensile and shear steel reinforcement (D500N grade)	Yield stress: 500N/mm^2
	Modulus of Elasticity: 200000N/mm^2
	Poison ratio: 0.3
Shear studs	Yield stress: 420N/mm^2
	Modulus of Elasticity: 200000N/mm^2
	Poison ratio: 0.3
Supporting steel girders	Yield stress: 300N/mm^2
	Modulus of Elasticity: 200000N/mm^2
	Poison ratio: 0.3

Table 2: Natural frequencies and associated modes of the slab panel

Mode of vibration	**Natural frequency (Hz)**	**Modal mass participation factor**					
		X	**R_X**	**Y**	**R_Y**	**Z**	**R_Z**
1st mode - transverse bending	2.5981	-3.66E-03	-4.72E+02	-2.92E-01	5.93E+00	2.19E-05	1.41E+00
2nd mode- transverse bending	4.1649	-1.52E-06	1.25E+03	8.80E-05	-2.05E+00	1.13E+00	-4.39E-04
3rd mode-transverse bending	6.8800	5.09E-02	2.77E+03	1.71E+00	-8.23E+01	6.24E-04	-1.92E+01
4th mode-torsion	9.7121	-1.35E+00	3.95E+01	2.44E-02	2.19E+03	-1.39E-06	4.94E+02
5th mode-transverse bending	12.3709	-1.78E-05	1.26E+03	-4.31E-05	2.78E+01	1.66E-01	1.06E-03
6th mode –transverse bending	20.8487	2.61E-03	-1.93E+02	-1.19E-01	-4.23E+00	9.70E-07	-2.60E-02
7th mode-torsion	21.1339	1.21E-04	1.89E+01	-3.59E-05	3.09E+02	-9.94E-04	6.11E-03
8th mode transverse bending	27.1507	7.13E-06	6.71E+02	7.81E-04	-1.87E+00	1.18E-03	-7.58E-03
9th mode- torsion	32.3012	4.68E-01	6.40E+01	3.93E-02	-7.58E+02	-5.61E-04	1.14E+02
10th mode- transverse bending	37.1369	-5.42E-05	2.01E+01	-6.61E-04	-5.79E+00	-4.85E-02	-2.99E-03
11th mode- bi-directional bending	38.8362	-2.68E-03	7.00E+01	4.35E-02	3.87E+00	3.01E-04	7.59E-01
12th mode-torsion	42.3631	-3.08E-04	-1.35E+01	2.86E-05	3.79E+02	2.33E-03	-7.31E-02
13th mode- transverse bending	46.0272	-6.96E-03	-5.24E+02	-3.23E-01	1.13E+01	2.11E-04	8.12E-01
14th mode-torsion	46.7509	-1.52E-01	-2.46E+01	-1.52E-02	2.45E+02	-2.34E-05	-9.59E+01
15th mode-torsion	51.2766	1.16E-02	1.27E+02	8.15E-02	-1.71E+01	-7.05E-04	1.12E+01

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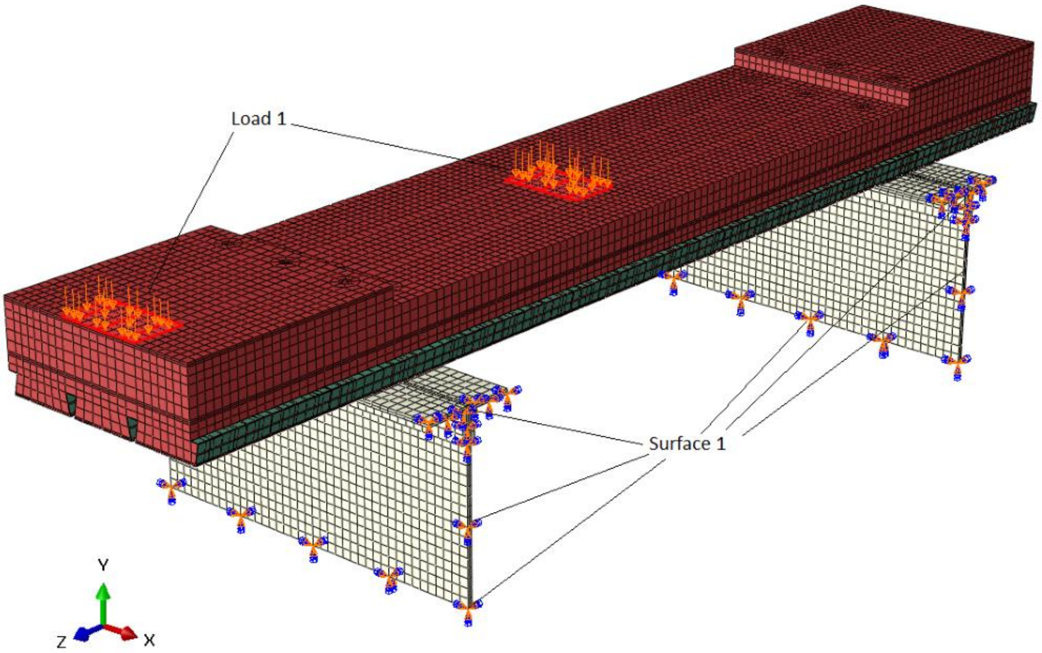
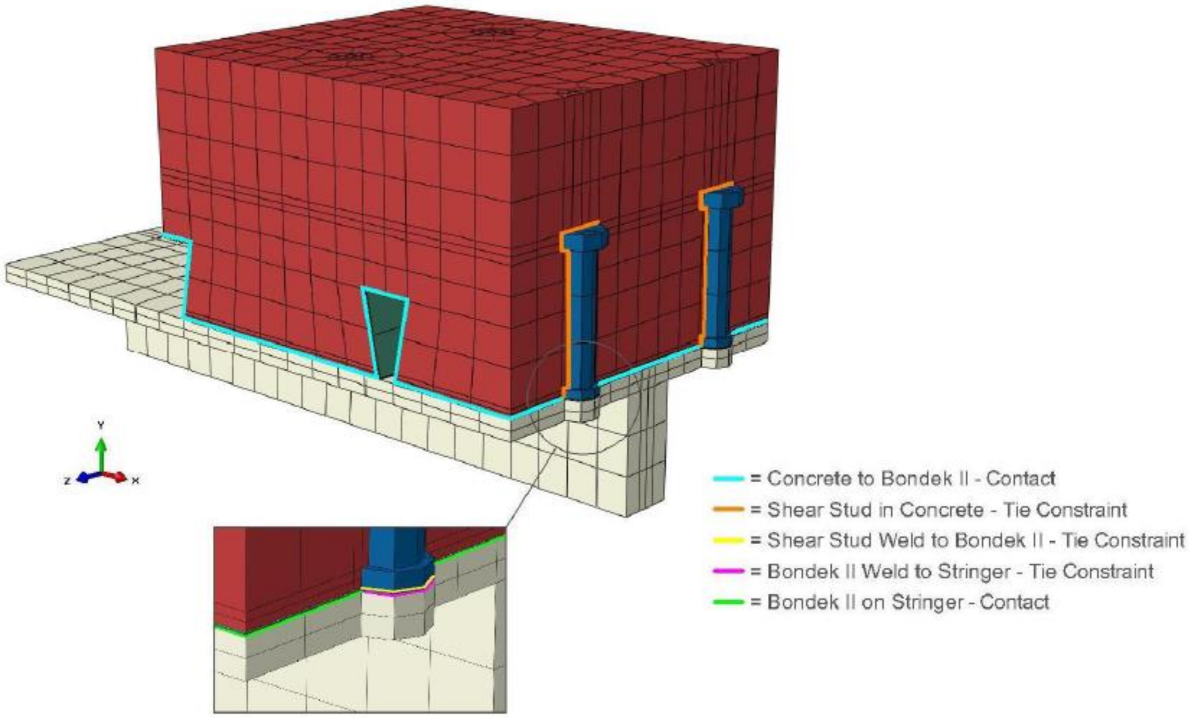
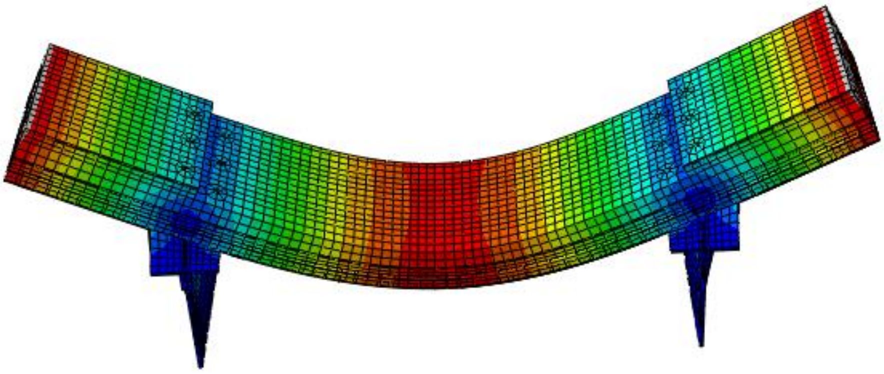


a) full model of the track slab over bridge girders

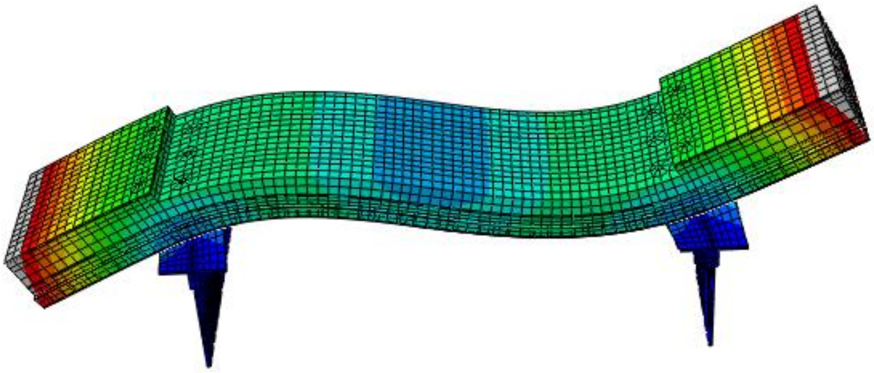


b) boundary condition and interfaces

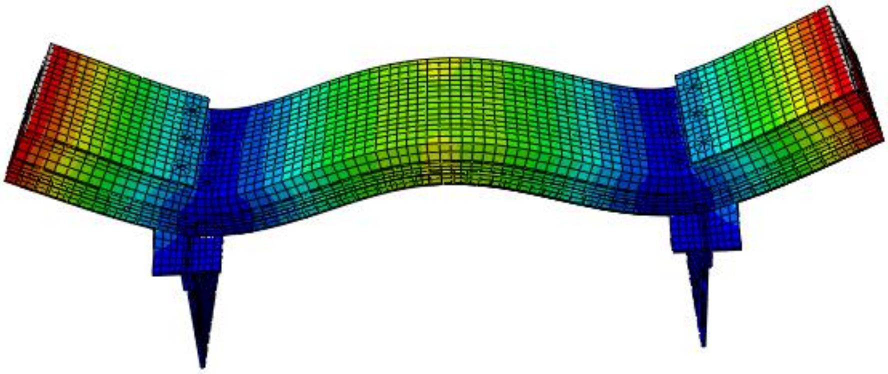
Figure 1: Model, contacts and interactions of composite track slab panel



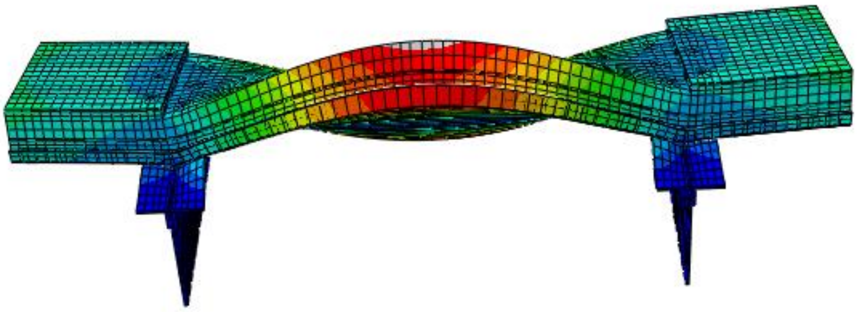
a) 1st mode – transverse bending, natural frequency 2.5981Hz



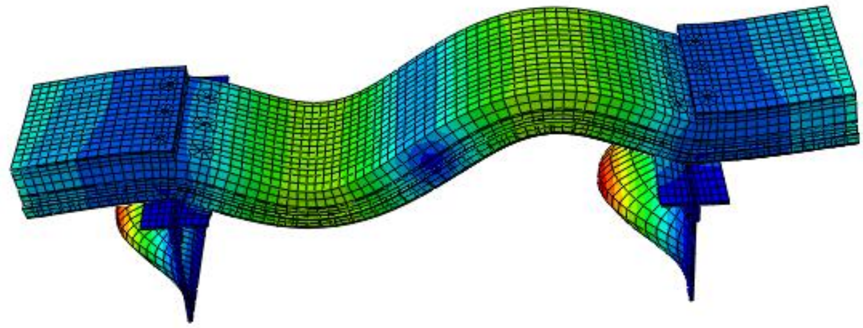
b) 2nd mode – transverse bending, natural frequency 4.1649Hz



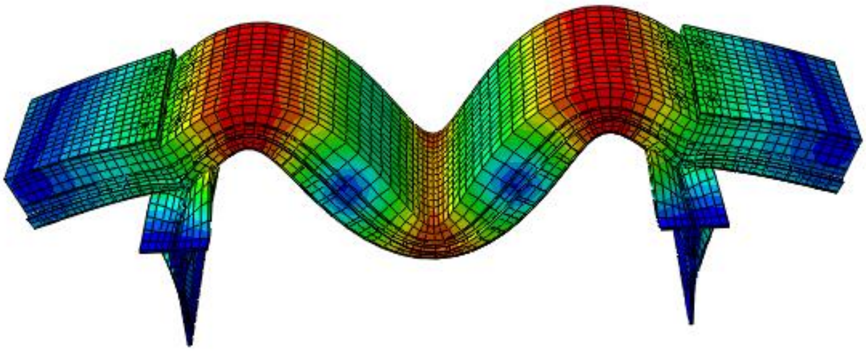
c) 3rd mode – transverse bending, natural frequency 6.8800Hz



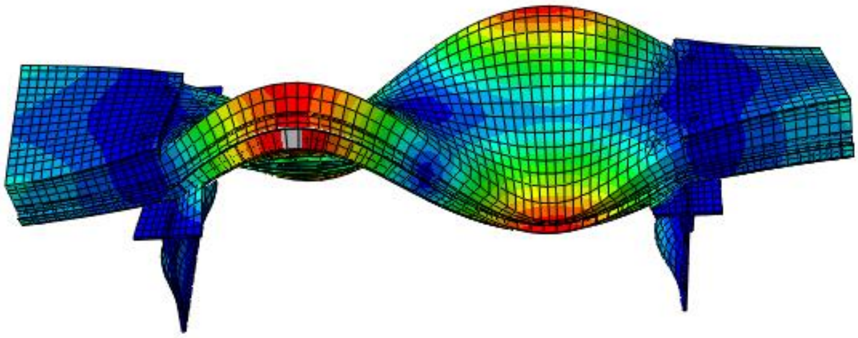
d) 4th mode – torsion, natural frequency 9.7121Hz



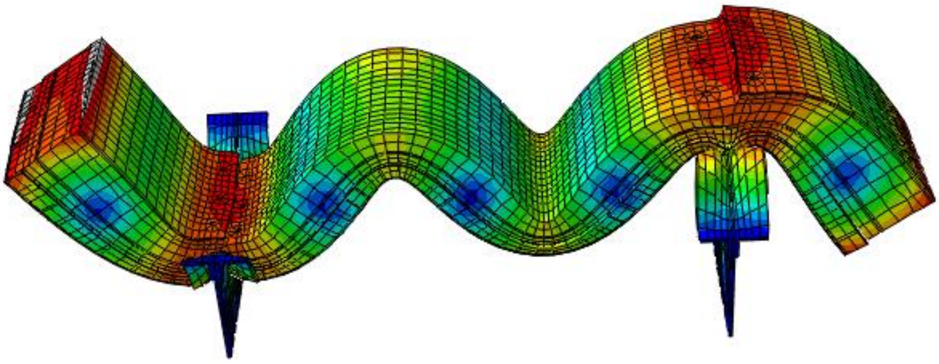
e) 5th mode – transverse bending, natural frequency 12.3709Hz



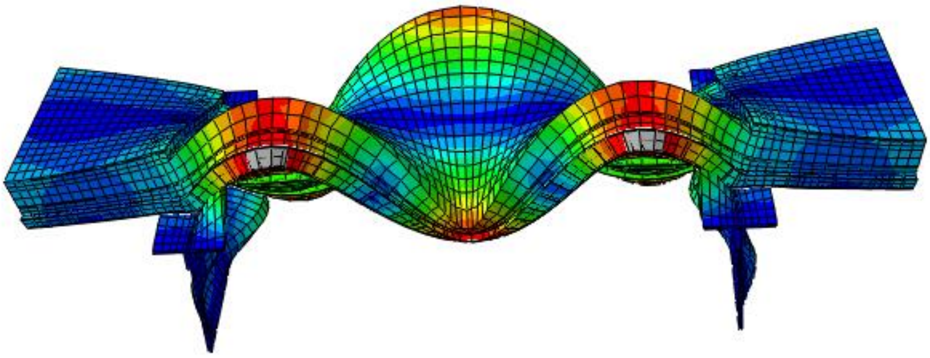
f) 6th mode – transverse bending, natural frequency 20.8487Hz



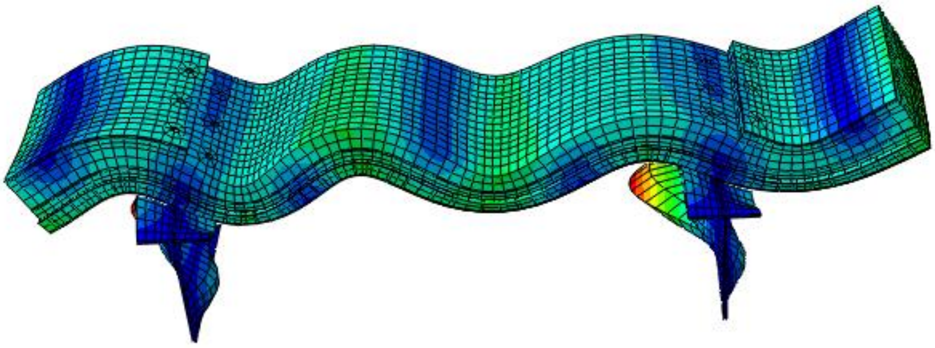
g) 7th mode – torsion, natural frequency 21.1339Hz



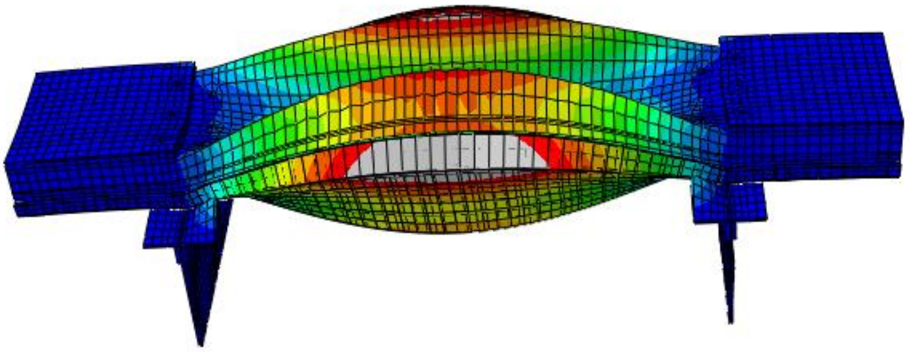
h) 8th mode – transverse bending, natural frequency 27.1507Hz



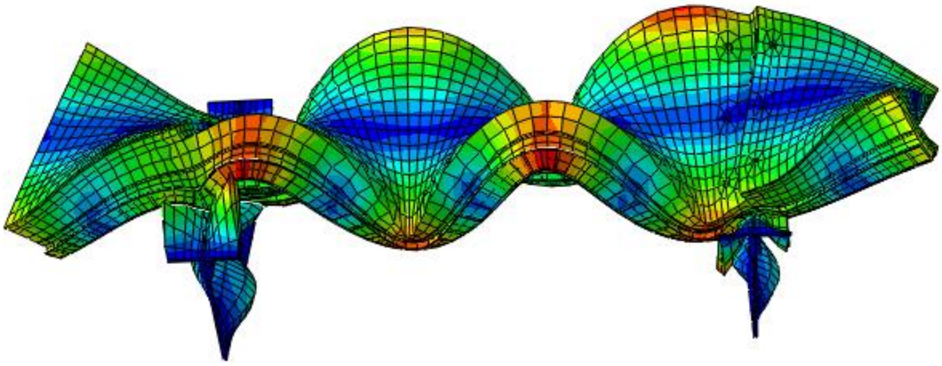
i) 9th mode – torsion, natural frequency 30.3012Hz



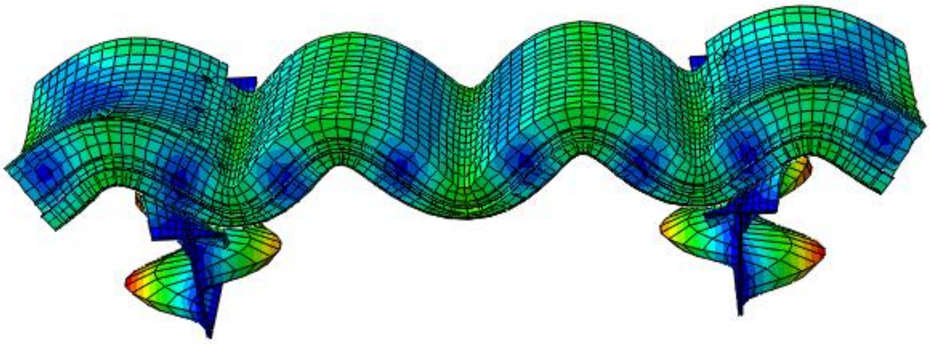
j) 10th mode – transverse bending, natural frequency 37.1369Hz



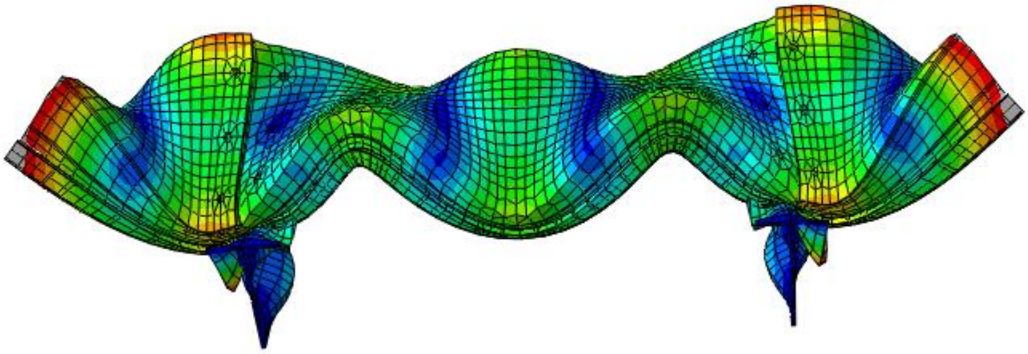
k) 11th mode – bi-directional bending, natural frequency 38.8362Hz



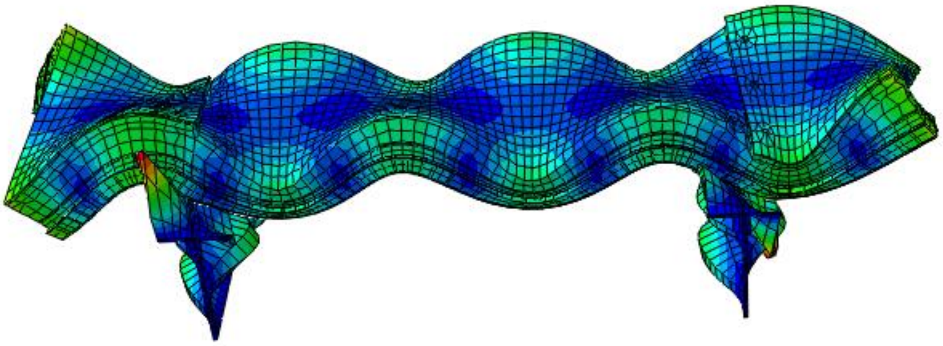
l) 12th mode – torsion, natural frequency 42.3631Hz



m) 13th mode – transverse bending, natural frequency 46.0272Hz



m) 14th mode – torsion, natural frequency 46.7509Hz



n) 15th mode – torsion, natural frequency 51.2766Hz

Figure 2 Corresponding modeshapes

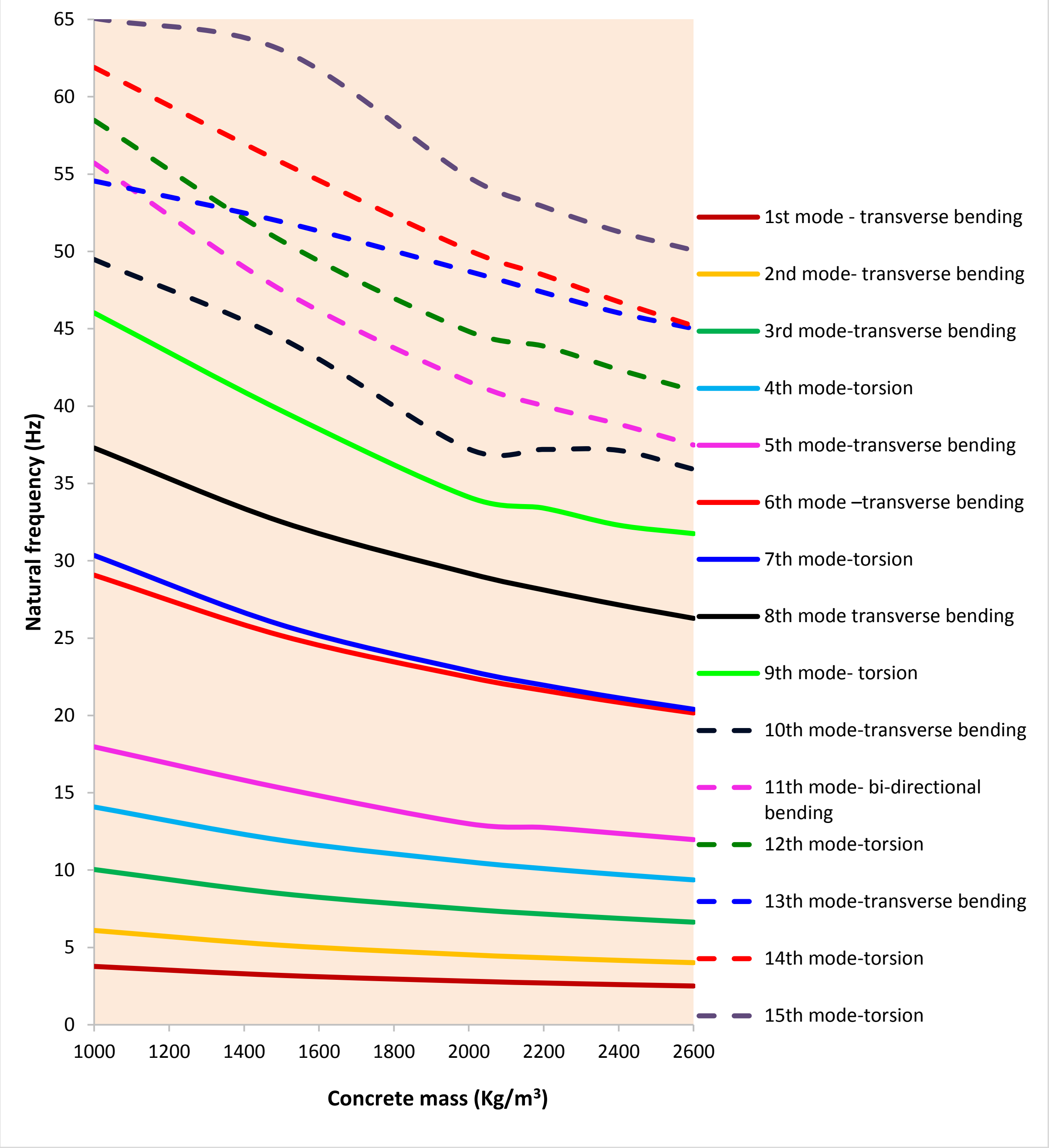


Figure 3 Modal crossover phenomena due to changes in mass