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Dynamic behaviour of steel–concrete composite beams with different types of shear connectors. Part II: Modelling and comparison

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ABSTRACT

In the first paper of these two companion papers an experimental study was undertaken to ascertain the dynamic behaviour of identical steel–concrete composite beams with differing shear connection systems. Two blind bolt connector types were used as shear connection systems in steel–concrete composite beams. Alongside these, a welded shear stud specimen, and a non-composite specimen were tested for comparison. In this, the second paper a Timoshenko beam model for steel–concrete composite beams is developed and is compared with the experimental results. An uncertain boundary condition is investigated using the Timoshenko beam model and an empirical relation between the displacements at the beam supports and the rotation of the cross section face is proposed.

1. Introduction

In the first paper an experimental study was carried out on a series of full-scale steel–concrete composite beams. The series comprised of three steel–concrete composite specimens and a non composite specimen for comparison. The composite specimens were designed with partial shear connection of approximately 70–80%. This is achieved with the use of three different shear connection types. The steel–concrete composite specimens were accompanied by a set of push tests designed according to [1]. Concrete cylinder tests for compressive strength f'_1 and Young's modulus E_1 were also undertaken. The major objective of the experimental series was to discern the suitability of, and differences between, the shear connection types. To this end all four full-scale steel–concrete beam specimens, accompanying push tests, and concrete cylinders were poured from the same concrete batch. This approach was taken to ensure similar material properties across the experimental series. Presented in this section are the details of the shear connection types, push tests, material tests, experimental specimens, and their collective results.

In this paper the dynamic behaviour of the steel–concrete composite specimens is simulated using a numerical model. There are many ways to approach modelling the dynamic behaviour of beams from the Euler Bernoulli approach such as [2] through to finite element methods such as [3]. However, it is mentioned by Nguyen in [4] that the effect of transverse shear on natural frequencies has had little investigation with only two studies being conducted, namely [5,6]. To add to the body of research the numerical model derived here builds on the work presented in [6–9]. [7] presented a one dimensional model of a composite beam is presented where the elements connecting the steel beam and the reinforced concrete slab are described by the means of a strain energy density function defined throughout the axis of the beam where the beams were forced to maintain equal transversal displacements. The work carried out by [8] questioned the validity of maintaining equal transversal displacement and showed that besides hindering sliding on the steel–concrete interface the shear connector also plays a crucial role in reducing the transversal displacements between the two sections. The analytical model was then developed in [9] based on [7] with no requirement for equal transversal displacements of the steel and concrete sections and included a strain energy density term associated with the relative transversal displacements between the two sections. The work presented by [6] points out that the models of [7,9] neglect the energy used to deform the connecting element. [6] goes on to include this term and makes comparisons between Euler and Timoshenko models using this connector definition.

Given the good result of the Timoshenko beam model presented by [6] the model presented in this paper is a continuation of that work. The work of [7,9,6] can be seen as the pursuit of a realistic description of the shear connector to gain a match between exper-

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Nomenclature

List of symbols

c	viscous damping coef
d	distance between shear studs
e_c	distance, concrete nuetral axis to interface
e_s	distance, steel nuetral axis to interface
f	frequency (Hz)
k	shear connector stiffness per unit length
$mc1$	nodal force m connector top
$mc2$	nodal force m connector bottom
$nc1$	nodal force n connector top
$nc2$	nodal force n connector bottom
$tc1$	nodal force t connector top
$tc2$	nodal forst t connector bottom
u	axial displacement
v	vertical displacement
y	distance from the nuetral axis
yA	analytical modal vector value
yE	experimental modal vector value
A	cross section area
B_i	bending mode i
E	Young's modulus
G	shear modulus
H	height of the steel section
J	inertia
K	shearing stiffness value
$\mathcal{L}$	Lagrangian
L	shear connector element length
$\mathcal{R}$	damping
S	frequency minimisation criteria
$\mathbf{T}$	kinetic energy
T	thickness
$\mathbf{U}$	strain energy
W_f	work
α	experimental constant
γ_{xy}	shear strain
δ_k	transverse displacement between stud ends
δ_μ	axial displacement of stud ends
ϵ_x	bending strain
ζ_1	rotation top of shear connector
ζ_2	rotation bottom of shear connector
η	damping coefficient
κ	shear correction factor
v	Poisson's ratio
ρ	density
σ_x	bending stress
τ_{xy}	shear stress
ϕ	modal vector
ψ	rotation of the cross section face
ω	frequency (Rad/s)
$()_0$	vector maximum value
$()_1$	related to concrete section
$()_2$	related to steel section
$()_a$	related to analysis
$()_b$	related to bending
$()_c$	related to shear connector
$()_{cr}$	comparison DoF r
$()_{dr}$	damaged DoF r
$()_e$	related to experiment
$()_f$	related to the flange
$()_s$	related to shear
$()_w$	related to the web
$()^e$	standard contribution
$()^d$	dissapative contribution
$()^T$	transpose

imental and analytical results has been the paramount goal. To isolate the behaviour of the shear connectors with as few variables as possible the experiments conducted by [7,9,6] were set up as a free-free boundary condition by suspending the specimens on cables. Whilst this is good for conducting research on shear connector behaviour it does little to address the behaviour of in situ composite beams. Using a simply supported boundary condition goes some way to addressing this issue however, it also introduces some uncertainties into the experimental results. Damping is added to the model in a modified version of that presented by [10] where the bending and shear stresses have damping components and a viscous damping term is added to the axial, bending, and shear terms. A model for an uncertain boundary condition is then proposed in order to match the experimental result which relates the vertical displacement at the supports to the rotation of the cross-section.

2. Theoretical model

In order to study the effect of varying parameters on the dynamic behaviour of the steel–concrete composite beams a numerical model must first be calibrated against experimental result. The experimental specimens were modelled as Timoshenko beams with a pinned–pinned boundary to reflect the simply supported condition of the experiment. The choice to use Timoshenko beam theory over Euler Bernoulli beam theory was made as the Timoshenko beam theory gives a better result. A comparison of dynamic analysis results for Euler Bernoulli and Timoshenko beam theory for a comparable specimen size was made in [6] and the Timoshenko beam model produced significantly better results. More recently a comparison and dimensionless parametric study was made in [11]. According to [11] the values of $E_1J_1/(E_1J_1 + E_2J_2)$ and $e_s/(e_s + e_c)$ are dimensionless and vary from zero to unity. As the difference between these two dimensionless parameters diminishes the difference between Bernoulli and Timoshenko beam theories becomes negligible. In the case of the experimental specimens presented in [12] there is a 13% difference in non dimensional values and so the result given by Timoshenko beam theory will be more accurate. The shear connector definition is taken from [6] whilst the solution method is the same as that of [6–9]. Referring back to the experimental results table in [12] it can be seen that there were some low levels of damping measured from the dynamic analysis. To reflect this in the numerical model, structural and viscous damping are included based on the method presented in [10].

Fig. 1 shows the deformations of a shear connection element due to nodal forces. The figure on the far right shows a shear connector subject to combined nodal forces and combined displacements. The equations describing the nodal forces on the shear connectors are then given by Eqs. (1)–(4) where $\mu = \frac{E_c A_c}{L_c d}$. A full explanation of this shear connector formulation can be found in [6]. From here on it is also assumed that $L_c = e_c$. This is the original assumption made in [6]. The lengths of the shear connectors are SS = 100 mm, BB1 = 95 mm, and BB2 = 80 mm. The uplift is resisted by friction along the bolts as well as by protrusions from the shaft of the shear connectors. Referring to [12] Figure [1] it can be seen that the geometries are complex. Calculating the effective length of the shear connector then becomes a complex task. Certainly to