Numerical investigations on static response of Laced Steel-Concrete composite slabs

A.Thirumalaiselvi
Masters of Technology in Engineering of Structures,
Academy of Scientific and Innovative Research,
CSIR-SERC, Chennai, India.
selvi@serc.res.in

N.An andavalli
Principal Scientist,
CSIR-Structural Engineering Research Centre
Chennai, India.
anandi@serc.res.in

***Abstract*— Laced Steel-Concrete Composite (LSCC) system consists of perforated steel cover plates, which are connected using reinforcing members and cross rods, and infilled with concrete. Reinforcing members are in the form of continuously bent rods known as lacing, which transfer shear continuously. This enhances the ductility and rotational capacity of the system. Experimentally, it has been demonstrated that LSCC beam possess high rotational capacity, which makes it suitable for structures resisting suddenly applied loads such as blast loads . In this study, an attempt is made to integrate LSCC flexural units into one way slab. Finite element model of LSCC unit is generated using a combination of solid, shell and beam elements. Finite element model is validated with the results obtained from experimental investigations carried out on LSCC beams. Responses from numerical simulation are found to match well with the experimental results. Same approach is adopted to model the proposed LSCC slab. Individual LSCC structural components are modeled separately and cross rods, which are provided on the outer sides of the steel cover plates to hold the lacings in position are extended throughout all the LSCC components so that all components will act as a single structural system. Numerical investigations are carried out on LSCC slabs subjected to static loading. Through numerical investigation, proposed system is found to be effective in resisting the externally applied loads.**

***Keywords*— Steel-Concrete composite, shear connector, Laced Steel-Concrete composite, Concrete damage plasticity model, finite element analysis**

I. INTRODUCTION

Steel-Concrete Composite (SCC) construction comprises a central concrete core sandwiched between two steel plates connected by shear connectors to form a composite unit. During the past few decades, there have been many research and development in SCC construction. The structural performance of SCC system has proven advantageous over other structural forms in application requiring high strength, ductility and energy absorbing capability. The most important component of SCC system is the shear connector, which transfers forces between steel and concrete. Different types of mechanical shear connectors such as headed stud, angle connector, Bi-Steel connector, plate connectors, J-hook connectors, cable shear connectors, bi-directional corrugated-strip-core system have been developed to bond steel plate and the concrete core [1,3,4,5].

Tonlinson et al. [1] developed Double Skin Composite (DSC) system using shear studs for immersed tube tunnel application under Conwy river. Though, DSC is similar to SCC construction, it was not popular due to difficulties in in-situ construction. Bowerman et al. [2] proposed SCC construction in which steel plates were connected by series of transverse bar connectors which were simultaneously friction welded at both ends. Disadvantage of this type of connector is the restriction on the thickness of concrete core. Sohel et al. [3] conducted test on SCC beams with angle type connectors to resist impact loads. Separation of plates was noticed after the impact test. A light weight SCC system with double J-hook connector has been developed by Liew et al. [4]. The J-hooks are placed perpendicular to each other on the top and bottom plates. This type of shear has been found to be effective in resisting outward buckling of compression plates when composite beam is subjected to flexural loads. SCC composite beam with bi-directional corrugated-strip-core system was proposed by Leekitwattana et al. [5], which is still under conceptual stage. In conventional SCC systems, shear connectors are welded to the steel cover plates. Performance of SCC system is highly influenced by the strength of welding. Recently, Laced Steel-Concrete Composite (LSCC) system, which avoids welding has been proposed by Anandavalli et al. [6]. It was found that LSCC beams exhibit enhanced rotational capacity and maintains structural integrity even at large deformations through experimental investigations.

Main aim of the present research is to develop LSCC slab system by connecting individual LSCC units, since slab forms basic component in many structures. Finite element model of the LSCC flexural unit, namely, beam is generated using a simplified approach. This approach uses solid, plate and beams to represent concrete, steel plates and lacings, respectively. Validation of finite element model is carried out using monotonic response obtained from experimental investigation. This model is extended to model LSCC one way slab. Behaviour of LSCC slabs is understood by conducting numerical investigations. Effectiveness of the proposed integration of individual units to form LSCC slabs is brought out through numerical investigations.

II. Laced Steel Concrete Composite (LSCC) System

LSCC system comprises of two steel cover plates connected using lacings and cross rods, and in-filled with concrete. This system avoids welding due to unique arrangement of lacings and cross rods. Figure 1 shows cross-section of LSCC system. Lacings are the main components that transfer load between plates.

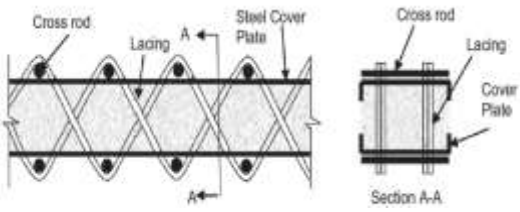


Fig. 1. Cross section of LSCC system

III. Numerical Investigation on LSCC Beam

A. Finite element model of LSCC system

Analytical modeling of complex problems such as analysis of composite structures is difficult without understanding its actual behaviour. Hence, numerical modeling of such problems have to be sought to. The static behaviour of LSCC beam is simulated using a finite element model. In conventional modeling of SCC structural components, solid elements are used to model concrete core, steel plates and shear connectors. But modeling using solid elements result in large degrees of freedom due to complex geometry. A simplified approach to model composite structures has been proposed earlier [7]. In this approach, concrete core, steel cover plates and shear connectors are modeled using solid, shell and link elements respectively. This approach is adopted in this study, since it is computationally efficient. The geometrical details of LSCC beam (of length 2400 mm) is shown in Table 1.

Concrete is created as a volume of dimension 150 mm x 300 mm x 2400 mm. Solid elements are used to discretize the concrete volume. Steel plates which are bent into lipped channel are geometrically modeled as areas of size 2400 mm x 300 mm and discretized using shell elements. Lacings which are bent at an angle of 45̊ are represented using wire elements. Cross rods of length 300 mm are represented using lines and wire elements. The finite element model is shown in Figure 2.

Table 1. Geometrical details of LSCC beam

Steel cover plate thickness	3 mm
Width of the cover plate	300 mm
Depth of web of cover plate	50 mm
Lip width of cover plate	25 mm
Cross rod diameter	10 mm
Lacing diameter	10 mm
Lacing angle	45̊
Spacing of lacings	200 mm
Concrete core thickness	200 mm

(a) Concrete core

(b) Steel plates with lacings

Fig. 2. Finite element model of LSCC beam

Solid elements are eight-noded hexahedral (3D) elements with 3 translational DOF per node. Shell elements are four-noded quadrilateral (2D) elements with 5 DOF per node. Beam elements are 2-noded linear (3D) elements with 6 DOF per node. There are 6912 solid elements (8 noded linear brick elements), 3456 shell elements (4 noded shell elements) and 864 beam elements (2 noded linear beam elements).

Concrete compressive strength is 50 MPa. Concrete damage plasticity model is used for representing the behavior of concrete. The parameters of concrete damage plasticity model are given in Table 2. Steel plates are made up of cold-formed steel with yield stress of 210 MPa and ultimate stress of 300 MPa. Lacings are made up of high strength steel bars. Bi-linear stress strain curve is used to represent the behaviour of reinforcing bar. Average yield stress and ultimate stress of bars are 400 MPa and 540 MPa, respectively.

Common nodes of steel plate and lacings are merged. Lacings are connected with cross rods at intersecting nodes. Connection of weld provides a fully bonded connection between two nodes. Lacings are embedded in concrete. The embedded element technique is used to specify an element or a group of elements that lie embedded in a group of host elements whose response will be used to constrain the translational degrees of freedom of the embedded nodes. In this study, truss elements in solid embedment model is used. Interface between concrete and steel plates is modeled using contact pair, which takes care of the compatibility between solid and shell elements at their interfaces. In this study, penalty method of contact algorithm is adopted. The steel plate is restrained from penetrating into concrete. Frictional coefficient, μ=0.45 is assumed between the steel and concrete contact surfaces. Node to surface interaction is given between nodes of cross rods and steel plate

International Journal of Civil & Structural Engineering – IJCSE
Volume 1 : Issue 1 [ISSN 2372 – 3971]
Publication Date : 09 January 2014

Table 2. Parameters of concrete damage plasticity model

Materials parameters	f_{ck}=50	The parameters of CDP model	
		β	38
Concrete elasticity		m	1
E(GPa)	19.7	$f=f_{bo}/f_c$	1.12
μ	0.19	γ	0.666
Concrete compression hardening		Concrete tension stiffening	
Stress (MPa)	Crushing strain	Stress (MPa)	Crushing strain
15	0	1.99893	0
20.197804	0.0000747307	2.842	0.00003333
30.000609	0.0000988479		
40.303781	0.000154123		
50.007692	0.000761538		

B. Validation of finite element model

Finite element model described in earlier section is validated with experimental results. Simply supported boundary conditions are simulated. Two point loading is given and loads are lumped at the nodes at 665 mm and 1035 mm distance from left support on the top plate and are applied in increments as shown in Figure 3. ABAQUS/Standard package is used for analysis of LSCC beams. Nonlinear static analysis is carried out.

The load versus displacement behaviour of the experimental study and numerical investigation of LSCC beam are depicted in Figure 4. From numerical investigation, load-displacement response is found to be linear upto 135kN, after which it becomes non-linear and attains its peak load at 170kN. Yield, ultimate load carrying capacities of beam found from experiment and numerical simulation are compared and tabulated in Table 3. Load-displacement responses obtained from numerical investigation are in close agreement with that of experimental results. Deformed shape of LSCC beam is shown in Figure 5. It has been found that local buckling of the top plate had occurred near the loading points. Further, it has been noted that the model using solid, shell and beam elements requires less time and retains accuracy.

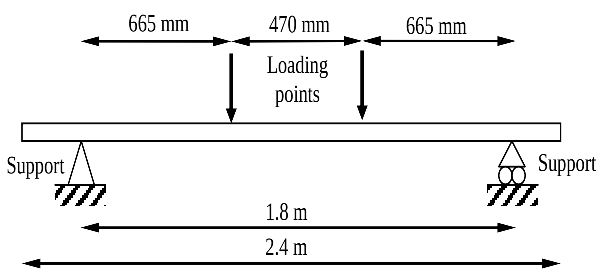


Fig. 3. Loading arrangement of LSCC beam

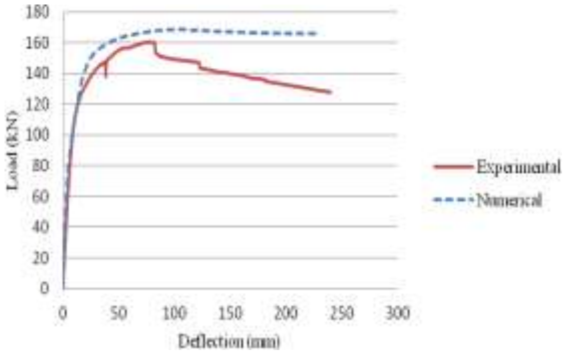


Fig. 4. Load-displacement response of LSCC beam

Table 3. Predicted and measured values of load carrying capacities

Values	Predicted by using finite element analysis	Measured values experimentally
Yield load	135 kN	120 kN
Peak load	170 kN	160 kN

Finite element analysis is overestimating the load carrying capacities of LSCC beams. Experimentally it has been found that the maximum support rotation achieved by LSCC beam is 13° when it is subjected to monotonic loading and is found to absorb more energy in each cycle when it is subjected to reversed cyclic loading. Ductility is also high when compared to conventional reinforced concrete which is evident from the Load-displacement response of LSCC beams. Energy absorption and ductility will provide information about the suitability of suddenly applied dynamic loads such as blast, impact or earthquake.

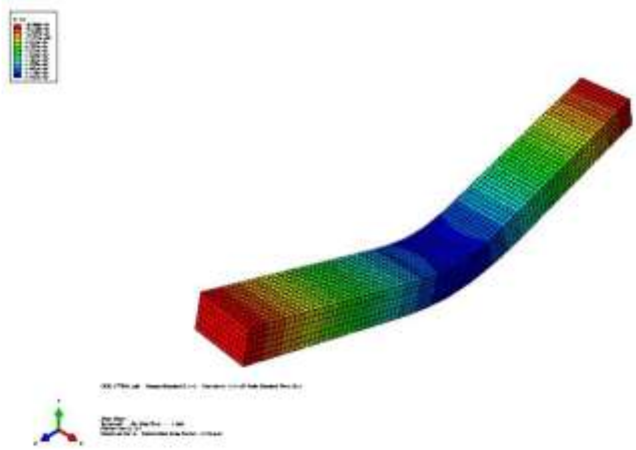


Fig. 5. Deformed shape of LSCC beam

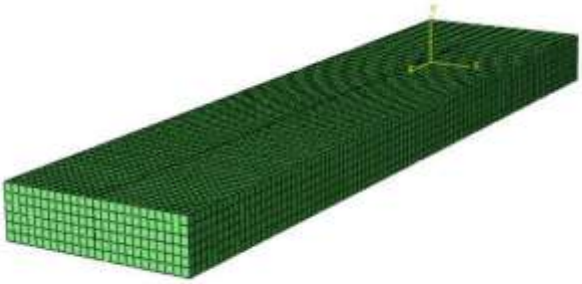
IV. Numerical investigation on LSCC slab system

A. Proposed LSCC slab system

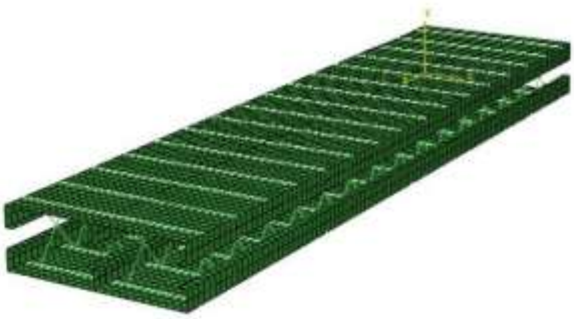
In construction of storage structures which are susceptible to accidental explosions, walls and roof slabs have to be made up of blast resistant material. Integration of individual units of LSCC beams into a one way slab will be useful in construction of blast resistant structure. LSCC slab system is conceptually proposed by connecting individual units of LSCC beam. Individual LSCC units are kept nearby and cross rods which are provided on the outer sides of the steel cover plates to hold the lacings in position are extended throughout all the LSCC units so that all units will act as a single structural system and serve the purpose of one way slab. Experimental investigations on LSCC slab will provide its actual behaviour under loading. But only few specimens can be tested. As an initiative numerical model to simulate the behaviour of LSCC slab is developed and finite element analysis has been carried out.

Two individual units of LSCC beam excluding cross rods are separately modeled as explained above. Finite element model with solid, shell and beam elements representing concrete core, cover plates and lacings respectively, is generated for numerical analysis. Finite element model of LSCC one way slab system developed by connecting two LSCC beam units is shown in Figure 6.

Behaviour of concrete is modelled through concrete damage plasticity model. Multi-linear and bi-linear stress strain curves are used for representing the cold formed steel and high strength deformed bars used for cover plates and lacings, respectively.



(a) Concrete core



(b) Steel plate with lacings, cross rod

Fig. 6. Finite element model of LSCC one way slab system

Interactions between steel cover plate and concrete core, connection between lacings and steel plate for each LSCC beams are provided in the same way as explained earlier. Extended cross rod (of length equal to width of slab) represented using wire element is created and lacings are welded with cross rods at intersecting nodes. Interface between concrete and steel plates is modeled using contact pair. Coulomb friction model and Penalty method of contact algorithm is adopted. Node to surface interaction is provided between nodes of cross rods and steel plate surface. Surface to surface interaction is provided between adjacent steel plates and concrete core materials. Contact interaction is defined between the adjacent steel cover plates and concrete core materials. The steel plates, concrete core materials are restrained not to collide with each other. Frictional coefficient, $\mu=0.55$ is assumed between the adjacent steel surfaces.

Simply supported boundary conditions are simulated. Uniformly distributed load is applied and are applied in increments as done in case of individual LSCC unit. Non linear static analysis is carried out.

B. Static response of LSCC one way slab

The load versus displacement behaviour of LSCC one way slab is shown in Figure 7. Deformed shape of the LSCC one way slab system is shown in Figure 8. From the deformed shape it has been noted that local buckling of cover plates occurred at the support locations. It has been found that extending the cross rod throughout the individual LSCC units is capable of keeping all the units together and while deforming all individual units deformed as a combined single unit. Thus, the effectiveness of the proposed system is brought out through numerical investigation.

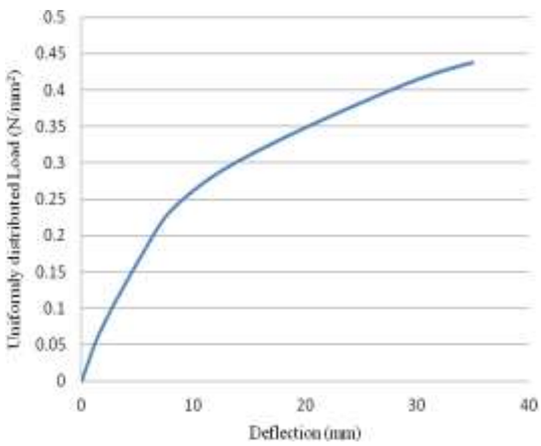


Fig. 7. Load-displacement response of LSCC one way slab

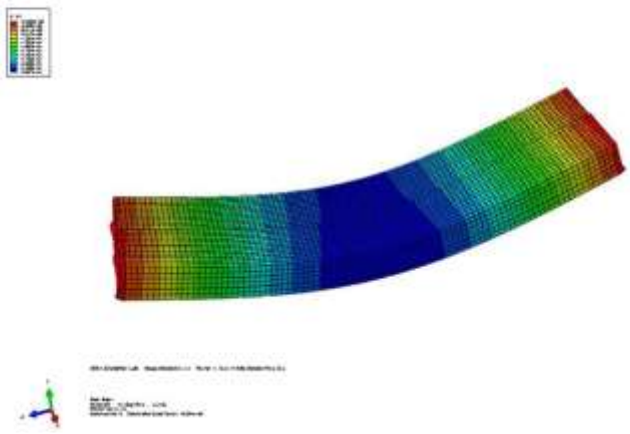


Fig. 8. Deformed shape of LSCC one way slab

V. SUMMARY

Ductility and structural integrity are essentially required for structures subjected to suddenly applied dynamic loads such as shock loads. In this study, finite element analysis of recently developed Laced Steel Concrete Composite (LSCC) beam is performed and load-displacement response obtained from finite element analysis are found to be in close agreement with that of experimental results reported in literature. In addition to this, LSCC slab system is proposed by integrating individual units of LSCC beam. Numerical investigations on static response of LSCC one way slab is carried out to bring out the effectiveness of the proposed system.

ACKNOWLEDGMENT

Authors thank staff of Shock and Vibrations Group for the help rendered in carrying out the numerical studies. This paper is presented with the kind permission of Director, CSIR-SERC, Chennai.

REFERENCES

[1] M.Tomlinson, A.Tomlinson, M.Chapman, H.D.Wright and A.D.Jefferson, “Shell composite construction for shallow draft immersed tube tunnels,” ICE International Conference on Immersed Tube Tunnel Techniques, Manchester, UK, April 1989.

[2] H. Bowerman, M. Gough, C. King, Bi-Steel Design and Construction Guide, Scunthorpe: British Steel Ltd., 1999.

[3] K.M.A.Sohel, J.Y.R.Liew, W.A.M.Alwis, P.Paramasivam, "Experimental investigation of low-velocity impact characteristics of steel-concrete-steel sandwich beams,” Steel and Composte structures: An International Journal, vol. 3(4), pp. 289-306, 2003.

[4] J.Y.R.Liew, C.G.Koh, K.M.A.Sohel, "Impact tests on steel-concrete-steel sandwich beams with lightweight concrete core," Engineering Structures, vol. 31(9),pp. 2045-2059, 2009.

[5] M.Leekitwattana, S.W.Boyd, R.A.Shenoi, "Evaluation of the transverse shear stiffness of a steel bi-directional corrugated-strip-core sandwich beam," Journal of Concructional Steel Research, vol. 67(2), pp. 248-254, 2011.

[6] N.Anandavalli, N.Lakshmanan, G.M.Samuel Knight, Nagesh R.Iyer, J.Rajasankar, "Performance of Laced Steel-Concrete Composite (LSCC) beams under monotonic loading," Engineering Structures, vol. 41, pp. 177-185, 2012.

[7] N.Anandavalli, N.Lakshmanan, Nagesh R.Iyer, G.M.Samuel Knight, J.Rajasankar, "A novel modelling technique for blast analysis of steel-concrete composite panels," The Twelfth East Asia-Pacific Conference on Structural Engineering and Construction, Procedia Engineering, vol. 14, pp. 2429-2437, 2011

[8] M.Xie, N.Foundoukos, J.Chapman, “Static tests on steel-concrete-steel sandwich beams,” Journal of Constructional Steel research, vol. 63(6), pp. 735-750, 2007

[9] H.D.Wright, T.O.S.Oduyemi, H.R.Evans, “The Experimental behaviour of Double Skin composite elements,” Journal of Constructional Steel research, vol. 19, pp. 97-110, 1991

.