CHAPTER 9

CONCLUSIONS

Ductility and structural integrity are essentially required for structures subjected to suddenly applied dynamic loads such as shock loads. Reinforced Concrete (RC), the most widely used construction material, possesses considerable mass per unit cost, excellent fire-resistance characteristics and can also absorb large amount of energy, if provided with proper detailing. However, one of the disadvantages of concrete is the possibility of spalling/scabbing when it is subjected to shock loading, which weakens the core and affects the integrity of the structure.

Among the alternative systems of construction, Laced Reinforced Concrete (LRC) and Steel-Concrete Composite (SCC) construction are found to possess properties that are promising for shock resistant structures. In this research work, a new form of Steel-Concrete Composite (SCC) system is proposed, after analyzing the limitations of existing systems. In addition to this, an equivalent stress-strain relationship for the analysis of Laced Composite Systems such as Laced Reinforced Concrete (LRC) and Laced Steel-Concrete Composite (LSCC) is derived.

A simplified approach to solve problems of equally reinforced RC / LRC structural elements subjected to flexure is proposed. Equations for obtaining the equivalent stress and strain characteristics for equally
reinforced LRC beams under flexure have been derived retaining the moment-curvature characteristics. The proposed approach is able to predict the peak load and ductility factors satisfactorily for LRC beams.

Laced Reinforced Concrete (LRC) has proven performance against blast loading. Steel-Concrete Composite (SCC) can be considered as an alternative material in view of complex detailing requirements in LRC storage structures particularly at the joints and also concreting poses problems. Performance of SCC under blast loading is studied using a simplified model to see the suitability of SCC as an alternate material to LRC. Steel-concrete composite panels can be constructed rapidly and can be best alternative for laced reinforced concrete for blast resistant construction. However, the welding of studs and placing concrete in between the parallel plates etc., will pose problems in construction. A system that can combine the advantage of steel-concrete composite together with lacing appears to be the best choice.

A new Laced Steel-Concrete Composite (LSCC) system is proposed. It consists of two thin steel cover plates connected using lacings and cross rods, and filled with concrete. This method of fabrication avoids welding in total. Monotonic load testing under four point flexure on two specimens, one with 45° lacing and another with 60° lacing, are conducted under displacement control mode. Experimental results indicate that both the beams exhibit almost similar strength performance, while the one with 60° lacing perform better in terms of deformation. Failure of the beams could not be achieved due to constraint in test setup on maximum displacement of actuator, the translation of the roller and the possibility of slippage of roller. At this stage, maximum support rotations achieved by LSCC beams with 45° and 60° lacings are 13° and 16° respectively.
Reverse cyclic load has been applied on two specimens of LSCC beams. Both the specimens are found to exhibit almost similar behaviour. Maximum load attained under both sagging and hogging moment conditions are found to be nearly equal. The envelope of cyclic load displacement response indicates softening response after reaching a peak value. Load drop in LSCC-60-C specimen is found to be about 11%, while in LSCC-45-C specimen it is about 16%. Spalling of concrete cover is a common problem with RC structural element subjected to reversed cyclic loading, because each element comes alternatively in compression and tension. But, in LSCC beams, steel cover plates prevent the spalling of concrete core also. Energy absorbed by the beam in each load cycle is calculated from the load deformation curves. Among the three load cycles at a level, it is always the first cycle which is found to absorb more energy. Energy absorbed in the second and in the third cycles are found to be in the range 70-95% and 65-85% respectively of that absorbed in first cycle for both the specimens. However, energy absorbed is estimated to be nearly the same for the load applied in the upward as well as in the downward directions.

Finite element model with solid, plate and link elements representing concrete core, cover plates and lacings respectively is generated for numerical analysis. Behaviour of concrete is simulated through concrete damaged plasticity model. Multi-linear and bi-linear stress strain curve are used for representing the cold formed steel and high strength deformed bars used for cover plates and lacings respectively. Load-displacement response obtained from numerical investigation are in close agreement with that of experimental results. Simplified material model proposed for LRC is extended for LSCC beams. This simplifies the entire task of modeling. Hysteretic model with pinching is used to obtain the
load-displacement response analytically. Energy absorbed is calculated from the load-displacement response and is found to be in close agreement with experimental results. This model is extended until 25% degradation in strength is achieved to get the cumulative energy absorbed by the LSCC beams. A model to predict the shear strength of LSCC beams is proposed based on the observation of strain variation in lacings.

Ductility of LSCC beams is comparatively more than LRC and conventional RC beams. Comparison of responses between LSCC beams and SCC beams with other form of connectors shows the advantage of LSCC beams. LSCC beams exhibit comparatively a better performance under cyclic load. Cyclic ductility factors of LSCC beams are substantially higher than that of LRC beams with and without fibres. Shear strength of LSCC beams are relatively higher than that of LRC beams. Engineering parameters for evaluating the cyclic behaviour of LSCC beams are suggested.

Based on the experimental, analytical and numerical studies carried out on LRC and LSCC beams in this investigation, following conclusions are made:

- A simplified approach for analysis of laced reinforced concrete (LRC) structural elements is formulated. Equations for obtaining the equivalent stress and strain characteristics for equally reinforced LRC under flexure have been derived retaining the moment-curvature characteristics. The proposed approach and simplified material model using equivalent stress-strain curve is able to predict the peak load and ductility factors satisfactorily for LRC beams. The
stress-strain characteristics can be easily adapted in any finite element software using multi-linear inelastic isotropic material model. The proposed approach is extended for solving a LRC slab subjected to uniform distributed loading. The model can be used for ordinary reinforced concrete by modifying the ultimate stress and strain values. This model can be extended for steel-concrete composite flexural elements. Equations for deriving the equivalent stress-strain curve are:

\[
M_i = M_i' + M_{i-1}'
\]

\[
M_i' = b \left( \frac{D^2 - d_{i-1}^2}{12} \right)^\alpha \left[ \sigma_i \left( 1 + \frac{D}{D + d_{i-1}} \right) + \sigma_{i-1} \left( 1 + \frac{d_{i-1}}{D + d_{i-1}} \right) \right]
\]

\[
M_{i-1}' = kM_{i-1} \left( \frac{d_{i-1}}{D} \right)
\]

From the above relations, equivalent stress, \( \sigma_i \) is evaluated.
Equivalent strain, \( \varepsilon_i \) is calculated from

\[
\varepsilon_i = \Phi_i \left( \frac{D}{2} \right)
\]

- New user friendly laced steel-concrete composite (LSCC) system possessing the essential properties for blast resistant construction, namely, ductility and structural integrity, is proposed. LSCC system comprises of thin steel cover plates provided with apertures / perforations, through which reinforcements in the form of lacings are introduced and held in position with the help of transverse / cross rods, after which concrete is filled in between the cover plates. This method of fabrication avoids welding in total.

- Experimental investigations on two LSCC beams are carried out under monotonic and reverse cyclic loads.
• Support rotations of more than 16° are achieved by LSCC beams

• Ductility of LSCC beam with 60° lacing is found to be more than that of beam with 45° lacing, while their moment carrying capacities are nearly equal.

• Under reverse cyclic loading, both the specimens are found to exhibit almost similar behaviour.

• Maximum load attained under both sagging and hogging moment conditions are found to be nearly equal.

• Envelop of cyclic load-displacement response indicates softening after reaching a peak value

• The pinching model for hysteretic behaviour with the formulation proposed by Ibarra et al (2005) is able to completely predict the cyclic behaviour of the LSCC beams. The following engineering parameters are suggested for evaluating the cyclic behaviour of LSCC beams:

\[
\begin{align*}
\alpha_c &= -0.01 \\
\alpha_s &= 0.25 \\
\gamma &= 250 \\
c &= 1.25 \\
\kappa_d &= 0.3 \\
\kappa_f &= 0.7 \\
\delta_c/\delta_y &= 3.15
\end{align*}
\]
- LSCC beam is found to have high rotational capacity as compared to that of LRC and RC beams and steel-concrete composite (SCC) beams with other form of connectors.

- It is observed from the variation of lacing strain with load in cyclic load reversals that only tensile strain are registered for both positive and negative displacements. Based on the above observation a model for shear resistance of LSCC beams has been proposed, which indicates that LSCC beams are unlikely to fail in shear even under low shear span to depth ratios. The shear strength, \( V_u \) is given by

\[
V_u = 4 \left( d_1 t_w \right) \left( \frac{f_u}{\sqrt{3}} \right) + f_t bd \sqrt{1 + \frac{2nA_s f_y \sin \alpha \cos \alpha}{bdf_t}}
\]

where
- \( d_1 \) = depth of web,
- \( t_w \) = thickness of web,
- \( f_u \) = ultimate stress of cold-formed steel,
- \( f_t \) = tensile stress = \( 0.3 \sqrt{f_{ck}} \),
- \( f_{ck} \) = cube compressive strength of concrete,
- \( b \) = width of the beam,
- \( d \) = depth of the beam,
- \( A_s \) = area of cross-section of lacing,
- \( f_y \) = yield stress of lacing steel,
- \( \alpha \) = angle of inclination of lacing,
- \( n \) = no. of parallel planes of lacings

Thus, a new form of steel-concrete composite beam is proposed and experimentally evaluated. LSCC system is found to possess the
essential properties, namely, high ductility, support rotation and structural integrity for resisting suddenly applied dynamic loads such as shock loads, which are the main objectives of the present research.

Following are the contributions made in the present research work:

- Simplified approach for analysis of laced composite system such as LRC, LSCC using an equivalent stress-strain characteristics derived based on the moment-curvature relationship.
- Evolution of new user friendly laced steel-concrete composite system possessing the essential properties for blast resistant construction, namely, ductility and structural integrity.
- Suggestion of engineering parameters to analytically evaluate the cyclic behaviour of LSCC beams.
- Evaluation of shear strength of LSCC beams.

The following are the suggestions for future research:

Parametric study on LSCC beams with varying diameter of lacing and thickness of plates have to be carried out. Some more specimens have to be tested to generate design guidelines. LSCC needs to be developed for planar elements by suitable integration techniques.

Application of LSCC beams for different loading conditions needs to be explored.