CHAPTER 2

REVIEW OF LITERATURE

2.1 GENERAL

This chapter reviews the literature on various structural forms with improved blast resistance. Literature on the studies of Composite Structural Components (CSC), Sacrificial Layered Construction (SLC), Sandwich Cores (SC), Profiled Steel Sheeting (PSS), Laced Reinforced Concrete (LRC), Steel-Concrete Composite (SCC) construction are presented in this chapter.

2.2 STRUCTURAL SYSTEMS FOR IMPROVED SHOCK RESISTANCE

Shock loads are short duration loads, causing extensive, instantaneous as well as progressive damage to structures and structural components. These loads may be concentrated over a small area, as in the case of impact or spread over a wide area as in the case of blast. Shock loads are highly transient in character and differ from other loads due to differences in the resistance mechanism activated in structures. When a structure is subjected to shock loading, an elastic design is seldom possible. Allowing the structure to undergo plastic deformations is appropriate to
arrive at an economical design. A permanent deformation of the structure, on the other hand may be undesirable if the structure is to be re-used.

Structural forms that have improved shock resistance can be categorised as follows:

- Composite structural systems such as Steel Fibre Reinforced Concrete (SFRC), Fibre Metal Laminates (FML)
- Sacrificial Layered Construction (SLC)
- Corrugated Metal Sandwich Core Construction (CMSCC)
- Laced Reinforced Concrete (LRC)
- Steel-Concrete Composite (SCC) Construction

2.3 COMPOSITE STRUCTURAL COMPONENTS

Blast resistance of a structural component can be improved by using high performance composite materials such as SFRC, FML, etc. In this section, literature pertaining to these material is briefly reviewed.

2.3.1 Steel Fibre Reinforced Concrete

Introducing randomly dispersed short steel fibres into the mixture can raise the survivability of concrete structures under shock loads. Studies on the behaviour of SFRC subjected to air-blast loads have been conducted by Lan et al (2005). Two types of steel fibres were used, one with enlarged ends and the other with hooked ends. Fibre concentrations of 0.5, 1 and 1.5% were used in the concrete mix. Failure pattern for rectangular slabs consists of a single line across the width at mid-length, while for square slabs typical diagonal yield lines represent the failure pattern. Panels with different types of steel fibre yield different degrees of
cracking and damage. It was also observed that panels with higher fibre concentrations do not necessarily have better resistance or possess fewer cracks than panels reinforced with lower fibre concentration. Nominal addition of steel fibres was found to overcome breaching. Advantages were compared with conventional concrete in terms of reducing cracking and crack propagation, minimizing spalling and retaining post-peak load-carrying capacity. Steel fibres substantially improve the structural integrity and also reduce the number of wider cracks. Presence of fibres also improve the ultimate ductility of structural element. It may be mentioned that special skill is required for the construction of SFRC structures. Steel fibres are costly, which is another constraint for a cost effective design. The use of SFRC is recommended for specific problems (spalling, penetration) in defense installations.

Silva and Lu (2007) have investigated the feasibility of increasing the blast resistance of RC slabs using innovative composite materials. Five slabs were tested under real blast loads. One slab was used as a control unit, while the other four slabs were strengthened with Carbon Fibre Reinforced Polymer (CFRP) and Steel Fibre Reinforced Polymers (SFRP), comprising of two slabs retrofitted on a single side and two slabs retrofitted on both sides. Test results indicated that there was no significant increase in blast resistance when the slabs were retrofitted on a single side. However, slabs retrofitted on both sides displayed a significant increase in blast resistance. It was also observed that slabs retrofitted with SFRP composite performed nearly the same as that of slabs retrofitted with traditional CFRP composite. As such, this new cost effective SFRP technology has shown a great potential for improving the blast resistance capacity of concrete structures.
Schneider and Reymendt (2008) examined the properties of DUCON (DUctile CONcrete), which is explosion resistant and fragment proof. Explosion tests performed showed high energy absorption and ductility. DUCON represents the combination of a high-performance or ultra-high-performance concrete and a micro-reinforcement from steel wire meshes. The micro-reinforcement is uniformly distributed across the cross section which results in a homogenous composition of the composite material. It consists of multiple layers of meshes with variable mesh width which are 3-dimensionally connected.

Experimental investigations on the behavior of plain reinforced concrete and normal strength SFRC panels subjected to explosive loading was carried out by Yusof et al (2010). Panels were subjected to blast loading generated by the detonation of 1kg of explosive charge located at 0.6 m. There was no significant damage on both front and back face of the specimen with 1.5% fibre and only two hair line cracks were developed at the back face of the specimen. This investigation indicated that the SFRC panel containing 1.5% of volume fraction gave the best performance under explosive loading, followed by concrete containing 1.0% fibres. However, it was observed that concrete containing fiber volume of 0.5% was not effective in resisting the explosive loading. Incorporating the fibres into concrete, significantly restrained the initiation and propagation of crack by the bridging effect and subsequently changed the failure mode from brittle to a pseudo-plastic mode.

2.3.2 fibre Metal Laminates

Few researchers have investigated the blast response of composite structures and lightweight materials. Fibre–Metal Laminates
(FML) are widely used as a blast resistant material. FML comprise of interleaved metal sheets and Fibre Reinforced Polymer (FRP). The most commonly used FML is GLARE, which comprises thin aluminium sheets and glass fibre reinforced epoxy.

Lemanski et al (2006) conducted experiments on Fibre Metal Laminates (FML) of varying thickness and material distribution subjected to localized explosive blast loading. Plastic deformation, debonding, delamination, fibre fracture and matrix cracking have all been identified as energy absorption mechanisms. Widespread debonding was particularly evident between layers. Comparison between different plates of similar overall thickness showed no significant improvement in blast performance with increasing number of distinct material layers. Thick and thin panels exhibited different front and back face deflections. Thin panels showed little debonding, while thicker panels had larger debonded areas.

Langdon et al (2007) studied the behaviour of aluminum alloy–glass fibre-reinforced polypropylene-based Fibre Metal Laminates (FML) subjected to localised explosive blast loading. Diamond and circular back face damage were observed and the shape was dependent on the panel thickness. Pitting, global displacement and tearing of the front face were identified. Examinations of sectioned panels revealed multiple debonding and delamination at interfaces, large plastic displacement and fibre fracture.

Observations from the experiments on Fibre Metal Laminates (FML) of varying thickness and material distribution were presented by Langdon et al (2007 a). Influence of staking configuration was also investigated. Some of the observations were related to wave propagation effects. Back face damage area was found to increase with
increasing impulse, and the shape of the debonded region was dependant on the panel thickness / number of layers. The diamond and cross debonding patterns arise due to the orthotropic properties of the GFPP weave. Spalling of the back face was due to the through-thickness reflected tensile wave propagation and the back face damage shape was influenced by the lateral wave propagation.

Lemanski et al (2007) presented a quantitative analysis of the experimental data on Fibre Metal Laminates (FML) subjected to explosive loading. The results indicated that thicker panels exhibited smaller displacements for a given impulse than thinner panels. Thinner panels exhibited behaviour that was closer to that of a monolithic metal plate. As the panel thickness increased, the behaviour deviated from monolithic plate response and debonding failures were seen.

The main disadvantage of Fibre Material Laminates (FML) based on thermosetting FRP are the long processing cycles, low fracture toughness and lack of repairability. Also, they cannot be used in large storage structures due to complexity of construction.

2.4 SACRIFICIAL LAYERED CONSTRUCTION

Blast resistant structure can be designed in layers, wherein the layer subjected to direct blast undergoes plastic deformations and hence reducing the energy transmitted to subsequent layers. In such a design the subsequent layers can be designed to work within the elastic limit. Hence, the structure can be designed in two layers that are sacrificial and non-sacrificial. The sacrificial layer may form the cladding layers and the frame or the grid structure can be non-sacrificial. The sacrificial part can be
modular and replaceable if damaged and hence, it can be an economical solution where impulsive load may be expected often.

Behaviour of layered sacrificial claddings subjected to blast loading was analytically studied by Guruprasad and Mukherjee (2000). Finite element analysis with step by step time integration was carried out. Layers absorbed energy by undergoing large plastic deformations before collapsing to a more stable configuration. The layers collapsed successively, one after the other. Substantial reduction in impulse transfer was observed at the base of the cladding structure as much of the energy was observed due to plastic deformations. A simple analytical model was also proposed for the sacrificial cladding structures.

Guruprasad and Mukherjee (2000 a) also proposed the sacrificial layer configuration. Each sacrificial layer was composed of a number of identical cells. The components of a unit cell were a base plate, a cover plate and a web plate. For multi-layered configuration, the base plate of the first layer formed the cover plate of the second layer and so on. The web plate had well-defined plastic hinge points. The proposed layer configuration was found to be very efficient in absorbing the blast. The layers of the sacrificial cladding collapsed successively. The first layer facing the blast load collapsed first. The second layer started collapsing only after the first layer had collapsed fully and this process continued. The sacrificial layer effectively isolated the non-sacrificial structure from the blast and the force transferred through the sacrificial layer during collapse was negligible. The collapse mode of the unit cell was always the same as predicted in the analytical studies. However, collapse of the layers was slower than that predicted in the analytical studies.
Theobald and Nurick (2007) have performed a numerical parametric investigation on sandwich panels consisting of thin-walled tubular structures in protective cladding for blast loading. The panels were constructed using 4, 5 or 9 thin-walled tubes as the core material. ABAQUS/Explicit was used to determine the influence of tube layout within the panel as well as tube geometry and top plate geometry on the energy absorption properties of the panel. It is important to note that the design study was performed under a constant impulse of 55Ns. This load was chosen so as to ensure the various modes of deformation. The resulting parametric study is accurate only under the given loading but gives a reasonable approximation of the global performance of panels within the expected impulse range. It is recommended that a study into the scaling aspects of the proposed panels be conducted to provide a more complete characterization of panel response.

Response of a sandwich cladding panel composed of square thin-walled metallic tubes under blast loading was investigated by Theobald and Nurick (2010). Irregular buckling modes were observed in all tests corresponding to crush distances well below the stroke of the tubes in the panel. Test panels corresponding to crush distances at or beyond the maximum stroke of the tubes resulted in symmetric buckling modes in nearly all tubes within a panel. This indicated that progressive, symmetric collapse of the core can occur despite buckling initiating at different locations on the tubes. In all cases panel crush distance increased with increasing impulse and decreased with an increasing number of tubes in the panel core.

The effect of core density and cover plate thickness on the blast response of sacrificial cladding panels have been investigated through blast
loading experiments and finite element modelling on structures with steel cover plates and aluminium foam cores by Langdon et al (2010). A range of foam core densities were examined, with 10, 15 and 20% nominal relative densities. The cover plate thickness greatly influenced the response of the sacrificial cladding. Cover plates that were 2 mm thick exhibited significant permanent deformations and variable percentage crush across the section, whereas the 4 mm thick cover plates were more rigid causing the core to compress uniformly. Considerable fracture of the foam was observed after blast testing, particularly for the foams with lower density. The effect of bonding of the cover plate to the core was also examined. Numerical simulations of the experiments were performed using ABAQUS/Explicit to provide insight into the response mechanism. It was shown through the finite element simulations that tensile fracture of the foam occurred during the unloading phase of response and that adhesion of the cover plate to the foam caused higher levels of cracking. This was consistent with the experimental observations.

2.5 CORRUGATED METAL SANDWICH CORES

Fleck and Deshpande (2004) and Xue and Hutchinson (2004) studied the behaviour of corrugated metal sandwich cores, which have proven excellent shock resistant properties, mainly due to their high longitudinal stretching and shear strength. The transverse strength of the corrugations is, however, dominated by buckling of the core members preventing full utilisation of the material. Steel corrugations, especially those having too thin core members at lower core densities (<150 kg m$^{-3}$) resulted in a very weak structure.
Côté et al (2006) performed an experimental and theoretical study on the behaviour of steel corrugations with densities in the range 260–720 kg m$^{-3}$. These corrugations typically failed by elastic buckling for the low densities and plastic buckling at the higher densities. Further, Rubino et al (2008) experimentally investigated the blast properties of corrugated cores and Y-cores with a nominal core density of 200 kg m$^{-3}$ which verified the beneficial blast resistance performance of corrugated cores.

Presently there is no good alternative for corrugated cores with lower densities. Fibre composite materials generally have significantly lower density than metal materials which enable the possibility of making low density corrugated cores with sufficient transverse strength. In the case of ultra lightweight cores, a novel corrugation concept has been developed by Kazemahvazi et al (2009) to prevent the core members from buckling. In this concept each core member is made in a sandwich configuration creating a hierarchical sandwich structure. Single-block shear tests were conducted. A novel corrugated composite core with superior strength properties had been developed, modelled and tested experimentally. The sandwich concept was used at two orders creating a hierarchical structure. Hierarchical structures exhibit a range of different failure modes, when the material and geometrical properties are altered. In order to validate the analytical model, failure mechanism maps were created and experiments were conducted for the different failure modes. Good agreement was found between the analytical predictions and the experimental observations.

If designed correctly, hierarchical structures can have higher strength to weight ratio on specific strength of the order of seven times as compared to its monolithic counter part. The difference in strength arises
mainly from the increase in buckling resistance of the sandwich core members compared to the monolithic version. The highest difference in strength is seen for core configurations with low overall density. As the density of the core increases, the monolithic core members get stockier and more resistant to buckling and thus the benefits of the hierarchical structure reduces.

2.6 PROFILED STEEL SHEETING

Boh et al (2005) presented a possible technique for providing passive energy dissipating system to increase the energy capacity, stiffness and strength of profiled blast walls. In essence, an impact barrier or brace is placed at a certain offset behind the blast wall. When subjected to certain level of loading, the blast wall will come into contact with the barrier that consequently absorbs some of the strain energy as well as altering the boundary conditions of the blast wall. Upon contact, the barrier helps to reduce the deformation of the blast wall and mitigate the strain development along the welded connections. The membrane effects in the panel will be reduced and thus delaying the tearing of the connecting welds. As such, the containment pressure and energy capacity of the blast walls can be enhanced. Furthermore, by permitting extensive plasticity to develop in both the blast panel and barrier, the impulse transfer to the supporting structure can be expected to be less than that of a stiffened panel. Another major advantage of this retrofitting technique is that costly shut down of the production facilities in the topsides can be avoided as site welding can be minimised as compared to the more traditional strengthening techniques. With appropriate planning, the proposed structural arrangement may also be suitable in new installations. However, the major drawbacks are the lack of
control against load variability and decrease of usage space in congested topside.

Although the impact barrier system is effective in enhancing the capacity of the blast walls, there is a need to ensure that the impulse transferred to the support structure is not excessive. The offset and the barrier section will also require careful selections so as to obtain an optimal blast wall system. Nevertheless the proposed system has offered an excellent alternative to the offshore industry for the purpose of rehabilitation and retrofitting of existing blast walls despite some of its inherent limitations which have also been highlighted.

Langdon and Schleyer (2005), conducted extensive experiments on one-fourth scale stainless steel blast wall panels with connections subjected to pulse pressure loading to study their modes of failure and blast resistance beyond the design limit. The panel design was based on the deep trough trapezoidal profile with welded angle connections at top and bottom and free sides. The study had shown that the connection detail can significantly influence the response of the panel to pulse pressure loading. The end restraint was a principal factor in the response of the panel. Consequently, the experimental work was focused on the connection detail. An analytical model was developed by Langdon and Schelyer (2005 a) to predict the response of walls, with semi-rigid connections subjected to blast loading. Strain hardening effects at the beam centre, where buckling occurred, have also been demonstrated. The test panels were shown to fail by localised buckling at the centre of the corrugations, and the analytical predictions compared favourably with the experimental results.
Profiled Steel Sheeting Reinforced Concrete (PSSRC) slabs have been widely used in the construction industry, since the Profiled Steel Sheeting (PSS) serves both as a permanent formwork and as an effective tensile reinforcement. Moreover, in blast resistant construction, damage due to concrete fragments ejecting at high speed on the tensile face is eliminated.

Debonding between the Profiled Steel Sheeting and concrete was not observed in the Profiled Steel Sheeting Reinforced Concrete (PSSRC) experimental tests conducted by Lan et al (2005). The slab thickness was varied from 150 to 300 mm. A number of PSSRC slabs with reduced rebar had minimum deflections. By ignoring the contribution of the profiled steel sheeting, these slabs would fail in a shear mode. In the practical design of protective structures, profiled steel sheeting should be considered as an additional reinforcement to reduce the rebar content.

Salim et al (2005) developed the analytical modeling and experimental evaluation of steel-stud wall systems under blast loads. The results of the static full-scale wall tests, as well as the components tests, are used to evaluate the structural performance of the walls and provide recommendations for blast-retrofit systems. The analytical and experimental static results are used to develop the static resistance function for the wall systems, which is incorporated into a single degree of freedom dynamic model. The dynamic model will enable designers to predict the level of performance of the wall system under any explosion threat level. The analytical model conservatively predicted the measured field results with a maximum difference of 20%. The study also discusses the performance of blast-retrofit wall systems under static and dynamic field tests simulating large vehicle bombs.
Profile steel sheeting provides an attractive and strong reinforcement to structures with similar threat, provided debonding of the profile steel sheeting from the concrete is avoided. However, delamination of the steel sheeting due to blast loading could be a major concern since it can affect the failure mode and capacity of PSSRC slabs/walls.

2.7 LACED REINFORCED CONCRETE (LRC)

Ductility of concrete elements can be improved by, suitable detailing technique. One such detailing of reinforced concrete elements is Laced Reinforced Concrete (LRC), which consists of continuous bent shear lacings along with longitudinal reinforcements on both faces of a structural element. Lacings provide reinforcement in the strut and tie directions and leads to very large ductility. A support rotation of 12° is suggested by TM5-1300 manual (1983) using laced reinforced concrete detailing. Based on experimental studies and numerical extrapolations, a series of charts have been provided by TM5-1300 manual (1983) for structures to resist the effects of accidental explosions.

Extensive experimental investigations were carried out by Parameswaran et al (1986) on LRC elements with cold worked deformed bars. Based on the studies the value of support rotation in LRC elements for blast resistant construction has been recommended as 4°. On a simply supported beam, this means a failure deflection of the order of 1/25 to 1/30 of span.

A mathematical model has been proposed by Lakshmanan et al (1991) to evaluate the failure rotations in reinforced concrete beams having
equal compression and tension reinforcement. These beams were provided with stirrups or transverse steel in the form of lacing with or without steel fibre reinforcement. Results of the experimental investigations showed that a majority of these beams failed by rupture of the tensile steel, while the remaining few failed by the buckling of the compression steel. The test results also revealed that the maximum percentage strain reached in the compression bars was of the order of 6 percent with high percentages of confining steel. A few of the beam specimens that were subjected to cyclic loading between positive and negative peak loadings failed by the buckling of the compression reinforcement and showed less failure rotations at the limit state of collapse.

A test programme to understand the behaviour of laced reinforced concrete structural elements under blast loading was undertaken by Keshava Rao et al (1992) to see whether the ductility realised in monotonic tests could be achieved under blast loading, whether an increase of 25% in strength as recommended can be used in design, and to study the yield patterns developed in different structural elements. Using 4° support rotation, and elasto-plastic and plastic approaches were used to design the test structures of LRC cantilever walls and cubicles. The crack patterns realised on cantilever walls were nearly horizontal, while that on cubicles were circular in the front and radial at the back faces. In spite of excessive cracking, concrete did not spall in any region. Also, the extraordinary deformability in case of even over-loading does not make the structure collapse. Thus, it had clearly established that LRC technique is very useful for blast resistant structures than conventional RC structures. As a result of the investigations, a handbook on the design of LRC for blast resistant design of structures has been brought out (STEC Pamphlet No. 21, 1996).
Rao et al (1998) proposed a new damage model for reinforced concrete elements which is consistent with accepted definitions of ductility and which takes into account at least two equal amplitude cycles at each displacement level. A total of 23 reinforced concrete beam elements were tested under monotonic and cyclic loading up to the ultimate failure of the specimens. The proposed model predicts 100 percent damage at the ultimate failure state of the element. The proposed damage index model can be extended to other structural elements, such as shear walls, columns, beam-column junctions, etc.

Investigations were carried out by Lakshmanan et al (2008) to study the performance of laced reinforced concrete beams with and without steel fibres under shear loading. Reversed cyclic shear loading tests were also carried out on the LRC beams with and without steel fibres. Beams with fibres showed improved energy absorption characteristics without much strength degradation. Peak load was improved with the addition of fibres. It was concluded that shear performance was significantly improved with addition of steel fibres and it is advantageous to provide steel fibres in shear critical zones.

Behaviour of LRC and its application for blast resistant design has been discussed in detail by Lakshmanan (2008). Response of LRC beam under low shear span to depth ratio is also presented. It was also observed that cyclic ductility is significantly lower than static ductility for these beams. Inclusion of fibres was found to increase the performance substantially under reversed shear cyclic loading. The versatility of LRC under blast loading was demonstrated by full scale testing.
Application of LRC in blast resistant structures has been demonstrated through actual blast trials by Anandavalli et al (2010). With the use of LRC in construction of the storage structures, separation distance between two storage structures has been reduced to 0.7 m/kg$^{1/3}$ from 2.4 m/kg$^{1/3}$ for conventional explosive storage structures. The acceptor storage structure could withstand the blast trial test and found to be serviceable after the blast. Thus, it is demonstrated that the LRC storage structure can reduce the separation distance by as much as 70% in a design based on unit risk principle.

Continuous inclined transverse reinforcement, in addition to enhancing the shear behaviour also arrests fragmentation of concrete and reduces flying debris in case of failure from external explosion. The detailing of laced reinforced concrete structures is quite cumbersome and must be carried out systematically for proper and smooth construction. The sequence of placing reinforcements for LRC is most important and should be clearly understood.

2.8 STEEL-CONCRETE COMPOSITE (SCC)

Steel–Concrete Composite (SCC) construction, also known as double skinned composite, is a structural system consisting of a concrete core, sandwiched between two relatively thin steel plates, connected to concrete by shear connectors. This form of construction combines the advantages of both steel and reinforced concrete systems to provide protection against impact and blast. It allows pre-fabrication of large panels in factory and enables rapid installation into the main structure significantly reducing fabrication cost and construction time. The two face plates act as permanent formwork during construction providing impermeable skins,
which are highly suited for marine and offshore applications. In addition, the flat steel surfaces can be readily protected, inspected and tested so that the integrity of the structure can be assured throughout its service life.

The structural performance of SCC system has shown its superiority over traditional engineering structures in application requiring high strength, high ductility, as well as high energy absorbing capability. Steel-concrete composite beams can bear tremendous structural loads; they are used often to protect buildings against extreme loading conditions such as earthquakes. However, the behaviour of SCC beam subjected to blast effects is not clearly known. Most of the previous studies have been focused on the ultimate strength behaviour of SCC sandwich structures under static or quasi-static loading. However, there have been a few studies on the impact behaviour of SCC composite structures.

An experimental study into the behaviour of double-skin composite (DSC) beams with mechanical shear connectors in the form of welded studs was presented by Oduyemi and Wright (1989). These beams were found to display very good flexural characteristics in terms of their ultimate strength and ductility. DSC elements formed from two steel skins connected to an infill of concrete with welded stud connectors were experimentally investigated by Wright et al (1991). Structural behaviour of these elements was observed to be similar to doubly reinforced concrete elements in many respects, except for possibility of steel plate buckling and flexibility of plate to concrete connection. Shear connectors also gave rise to more discrete cracking in DSC elements subjected to flexural loading.

Design rules were proposed by Wright et al (1991 a) from the basic behaviour established through tests on model scale specimens. Wright
et al (1991 b) presented a closed form solution for the analysis of simply-supported double skin composite beams, taking into account the flexibility of connection. The methods also covered the effects of concrete cracking and non-linear connector behaviour using a step-wise linearisation technique.

Bi-Steel is a system of double skin steel–concrete–steel construction. Units comprising of steel plates connected by an array of transverse friction welded shear connectors and filled with concrete was studied by Bowerman et al (1999) and Bowerman et al (2002).

The experimental and numerical analysis of the shear strength of each friction weld subject to push out load was studied by Clubley et al (2003, 2003 a). Finite element analysis using nonlinear discrete element models have been used to examine the local behaviour of concrete filled panels. Results from finite element analysis have been compared with experimental data for accuracy and behaviour trends. Conclusions drawn indicate the presence of several possible failure modes in the shear connection. Experimental studies were also conducted to examine the strength and stiffness of shear connector rods when the concrete was subjected to a shearing action relative to the steel plates. Testing shows that the Bi-Steel system has significant shear capacity for push-out loading. The shear strength is affected by several parameters, including plate spacing, connector spacing and shear connector diameter. From the load–deformation relationships it can be seen that steel–concrete–steel panels have high ductility and deformation capacity. For thick steel plates the failure can be brittle if shear connector numbers are small. The overall failure will be initiated by the shear failure of individual friction welds. For thin plates the failure is ductile, with a tear developing in the
plate around the weld following large localised deformation of the plate. Numerical modelling using a combination of smeared and discrete element interfaces between the steel and concrete surfaces have been shown to accurately model physical behaviour. Use of numerical modelling has provided data which was not readily available from the laboratory and which confirmed that panel behaviour was a function of panel geometry.

Details of an extensive large-scale test programme on a series of composite structural components subjected to explosive loading are presented by Lan et al (2005). The test components include conventional reinforced concrete slabs, steel fibre reinforced concrete slabs, profiled steel sheeting reinforced concrete slabs, steel–air–steel sandwich panels and steel–concrete–steel sandwich panels. Seventy four specimens were tested using seventeen detonation phases; with charge weight ranging between 8 and 100 kg of bare high explosives and each at stand-off distance of 5 m. The main parameters observed in the tests were the generic construction form of the materials and slab thickness. Failure modes of each type of specimens were recorded and are presented. Major conclusions are drawn on the safety aspect of these components in resisting explosion loading. Adding concrete to a hollow steel sandwich panel can significantly increase its blast resistance. Although concrete increases the cost by about 10%, significant deflection resistance against blast loading was observed. In the event of a repeated blast, the concrete in-fill panel provides improved resistance compared to hollow sandwich panels.

Experimental investigation on the static behaviour of steel-concrete composite beams with Bi-steel connectors have been carried out by Xie et al (2007). Eighteen beams having a range of span, depth, plate shear, bar tension and concrete shear were tested. All the beams
had a width of 400 mm and there were two connectors across the width with transverse spacing of 200 mm. All bars in the beam were equally spaced longitudinally between the supports. The beams had either two or three pairs of connectors between the mid-span and end pairs. The beams were filled with ready-mix concrete of Grade C40/50, which would nominally give cylinder strength of 40 MPa and cube strength of 50 MPa. Four elementary modes of failure observed were tension plate failure, bar tension failure, concrete shear failure and bar shear failure. After the concrete was removed, the failed beam showed a combination of some of these elementary modes of failure. Plate rupture did not occur, but very high plate strains led to concrete and/or bar failure; that has been designated “tension plate failure”. The tests confirmed that for ductile failure, beams should be designed to fail by yielding of the tension plate.

Liew and Sohel (2009) investigated a new concept for designing composite structures comprising of lightweight concrete core sandwiched between two steel plates which are interconnected by J-hook connectors. The hook connectors were capable of resisting tension and shear, and their uses were not restricted by the core thickness. Push-out tests confirmed that the shear transfer capability of J-hook connector is superior to the conventional headed stud connector in achieving composite action between steel plate and concrete core. Twelve sandwich beam specimens were tested to evaluate the flexural and shear performance subjected to static point load. Parameters investigated include degree of partial composite, concrete with and without fibres and concrete strength. Using Eurocodes as a basis of design, theoretical model was developed to predict the flexural and shear capacity considering partial composite and enable construction of sandwich structures with J-hook connectors. The predicted capacity was generally conservative if brittle failure of connectors can be avoided. Test evidence
also showed that inclusion of 1% volume fraction of fibres in the concrete core significantly increases the beam flexural capacity as well as its post-peak ductility.

Liew et al (2009) further extended the work to study the performance of sandwich beams with J-hook connectors under impact loads. Impact tests were carried out by dropping free weights on to sandwich beams to investigate their structural response against impact loads. Test results revealed that the proposed J-hook connectors provide an effective means to interlock the top and bottom steel face plates, preventing them from separation during impact. The use of fibres in concrete core and J-hook connectors for composite action enhances the overall structural integrity of the sandwich beams when compared with those without such enhancement. An elastic-plastic analysis method is developed to predict the force-indentation relationship of sandwich sections subjected to local impact. Dynamic analysis based on the local force-indentation relationship is carried out to predict the impact force and global response behaviour of the sandwich beams. The predicted results are compared with those obtained from the tests to validate their accuracy so that they can be used to evaluate the performance of sandwich beams under low velocity hard impact.

A numerical parametric study has been conducted by Li et al (2009) to investigate the behaviour of SCC beam under localised blast loading. Due to the involvement of complex interactions between the steel and concrete in SCC type of components, a nonlinear finite element model is deemed to best suit the purpose of the analysis. Using an appropriate Finite Element model, a detailed nonlinear response and the development of failure modes, were studied. Results from the study showed that the
response of SCC beam under localised blast loading is very different from that under conventional loading. The position of localised blast loading has a significant effect on the moment and shear forces at the supports of a SCC beam. However, the maximum moment, shear force and deformation over the whole beam vary slightly. It is found that under a localised blast load SCC beam failed mainly in three failure modes, namely, local concrete damage, flexural failure and punching shear failure. Punching shear failure is a brittle failure mode and should be avoided in the design of SCC beam against localised blast loading. Based on the parametric studies through the finite element approach, a simplified method using equivalent SDOF system was proposed for predicting the maximum deformation of SCC beam subjected to localised blast loading.

Andrews and Moussa (2009) have considered the situation of air blast loading of a lightweight foam core sandwich panel with composite face sheets. The analysis included the structural response of the composite panel and provided predictions of the failure mode and failure conditions. The failure modes observed were core shear failure and face sheet wrinkling. A method of inelastic buckling analysis of thin-walled sections of composite T-section beam is developed by Vrcelj and Bradford (2009).

Long-term behaviour of composite steel concrete beams with partial interaction was presented by Al-Deen et al (2011). Considerable increase in beam deflection was observed due to concrete creep and shrinkage in all the beams. Further, influence of time effects on the ultimate response of steel-concrete beam was studied by Al-Deen et al (2011 a).
2.9 SUMMARY

A critical review of literature on blast performance of structural components of various forms have been carried out. Among these alternative systems of construction, Laced Reinforced Concrete (LRC) and Steel-Concrete Composite (SCC) construction are found to possess properties that are promising for blast resistant design of large sized structures.