*Transactions*, **SMiRT-24**
**BEXCO, Busan, Korea - August 20-25, 2017**
**Division IX (include assigned division number from I to X)**

# BEHAVIOR OF FIBER REINFORCED STEEL CONCRETE SYSTEMS UNDER HAZARD LOADS

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## ABSTRACT

Steel-Concrete (SC) double skin composite is a structural form that typically consists of concrete filled between two steel face liner plates, which act compositely via tie bars and shear studs. It is quickly gaining popularity in the nuclear power industry worldwide mainly because of their many advantages such as modular and accelerated construction, cost effectiveness, good strength properties for given size members. The main problems associated with SC plated panels are related to the extensive locked-in shrinkage cracks that appear in the unreinforced concrete core under high thermal loads, particularly in the case of nuclear structures, as well as the limited strength and ductility under blast and earthquake loads. The aim of this proposed work is to resolve these issues by developing an enhanced SC composite structure employing fibre concrete instead of the traditional normal concrete.

The addition of Steel Fibers (SF) to concrete has been widely studied in the past decades as a mean to control its crack behaviour and maintain its ductility in tension. Further, since the discovery of carbon nanotubes/fibers (CNT/CNF), they have been also considered as efficient fibers to be used in construction materials such as concrete. In addition, due to tunnel conductivity effect, CNF concrete exhibits properties necessary for self-health monitoring ability.

This study aims to expand upon the use of SF and CNF concrete in structural members focusing on SC systems. The use of both SF and CNF fiber reinforced concrete in SC systems could potentially be advantageous in many aspects such as performance enhancement of the structure under normal loading conditions as well as in case of hazard loads. The study includes materials and large-scale experimental tests and analytical studies to evaluate the performance of fiber-reinforced SC specimens. The numerical work aims to develop a new finite element model to simulate the seismic and impact behaviour of SC structural members using fiber beam element formulations. The study confirmed the benefits gained using the enhanced SC systems.

## INTRODUCTION

Steel fiber reinforced concrete (SFRC) is widely used in reinforced concrete construction due to its high toughness, tensile and flexural strength. It has also been observed from recent experimental work that the use of carbon nano-fiber (CNF) in reinforced concrete members enhances the mechanical behaviour of material by reducing the size and propagation of cracks (Makar and Beaudoin, 2003, Xiao et al., 2003, Ji, 2005, Sanchez and Sobolev, 2010, Metaxa et al., 2013, Mullapudi et al., 2013). The main focus of this study is to investigate the effect of steel fibers (SF) and carbon nano fibers (CNF) on the performance of steel-concrete-steel (SC) double skin composite members under hazard loading. The structure of the nano tubes is based on graphite sheets rolled into a tube shape while carbon nanofibers are made of stacked cone shapes which have exposed edge planes along their surfaces.

To date, the research on nano fibers have mainly been focused on the cement paste and it is concluded that the properties of the cement paste can be enhanced by increased compressive strength, lower thermal conductivity, increased durability, and increased electrical conductivity for health monitoring purposes (Yazdanbakhsh and Grasley, 2011).

An initial material test is conducted on CNFRC with 0.5% and 0.75% of fibers by volume of the binder. The CNF is mixed with water and superplasticizer and then sonication techniques are used to properly disperse it. Compression and split tensile tests were conducted on cylinders of H200×D100 mm, and flexural beam tests were conducted on 500mm span specimens as shown in Fig. 1.

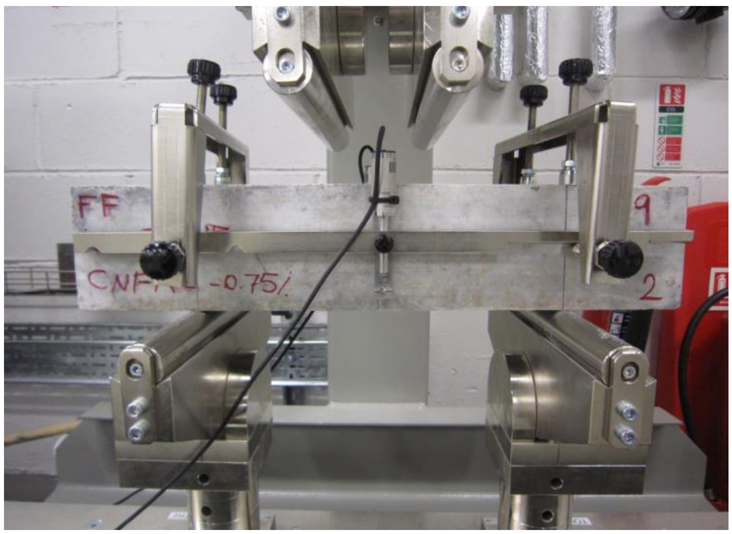

Figure 1. Flexural test set up

The strength of the material is derived and compared to normal concrete. A comparison of the results for compression test is shown in Fig. 2.

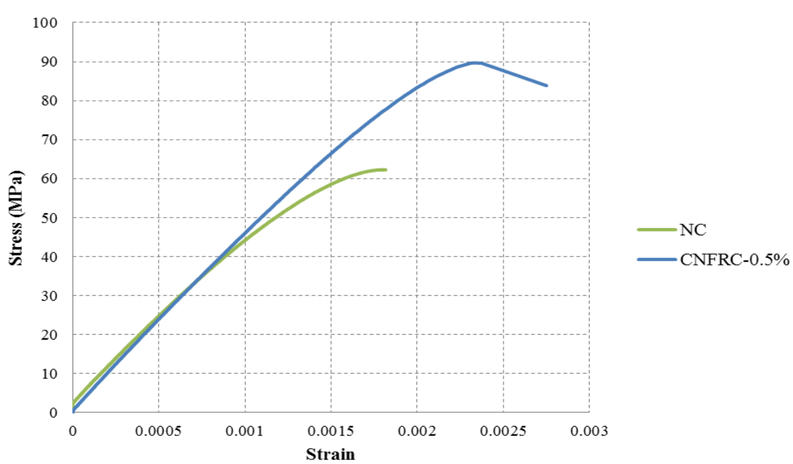


Figure 2. Cylinder Compression Test Results

The results of this simple comparison show that concrete with similar proportions and constituents has higher strength under compression by 38.8%, and the tensile strength was also increased by 8%. Fig. 3 shows the CNF concrete beam at failure. Further tests are being conducted to evaluate the ductility enhancement of the concrete by using such fibers in the concrete.


Figure 3. Failure of CNF Concrete Beam

For this research study, the type of structural member to be investigated is known as Steel Concrete sandwich wall, which is used for heavy structures (McKinley and Boswell, 2002, Ozaki et al., 2004, Varma et al., 2011). During recent decades steel-concrete (SC) composite walls have gained popularity due to their structural efficiency and construction speed. Steel faceplates works as a formwork and sandwiched unreinforced concrete serves as stiffener with studs and tie bars to prevent buckling along with their flexural and shear resisting capability. This arrangement facilitates to delay the buckling of the steel plate and inelastic buckling mechanisms gets activated which in turn provides larger shear resistance with more energy dissipation capacity compared to that of conventional reinforced concrete (RC) and steel plate shear wall. This will result in smaller thickness and less weight of composite shear wall. The smaller footprint of the composite shear wall is very advantageous from an architectural point of view providing more useable floor space. Moreover, the desirable performance would be when the damage to composite shear walls can be limited to shear yielding of steel plates with almost no cracks in the concrete wall or damage to other elements of the system. High performance concrete such as steel fibre reinforced concrete (SFRC) and carbon nano fibre reinforced concrete (CNFRC) with appropriate confining arrangement can act as a catalyst to achieve this kind of performance. As a result, the composite shear wall will become an effective dissipative mechanism which will result in providing improved performance level keeping sufficient margin of deformation capacity with respect to collapse prevention level.

## FIBRE BEAM ELEMENT

Mullapudi and Ayoub (2010) developed a mixed based fiber beam-column element adopting the softened membrane model, SMM (Hsu and Zhu 2002), where shear deformation is modelled using Timoshenko beam type approach along the element with the assumption of plane sections remain plane after deformations. One of the key elements of SMM model is the softening coefficient ($\zeta$) which is a reduction factor of compressive strength with increasing uni-axial principal tensile strain. It is a ratio of experimentally determined compressive strength under tension-compression sequential loading on a RC panel to experimentally determined uni-axial compressive strength of RC cylinder. Having experimental data of compressive strength for various levels of cracking measures i.e. tensile strain (sequential loading); Belarbi and Hsu (1995) proposed a mathematical equation of softening coefficient relating the uni-axial tensile strain for RC panels (Eq. 1).

$$\zeta = (5.8/ (fc')\ \hat{}0.5)*(1/(1+400*\varepsilon)\hat{}0.5)*(1-(\alpha/240) < 0.9 \qquad \text{Eq. (1)}$$

Where
fc' = Uni-axial concrete compressive strength
ε = smeared uni-axial tensile strain
α = deviation angle between applied stress angle and rotating angle

In a similar way, Tadepalli and Hsu (2010) has carried out several tests for SFRC panels and found a relation between the experimental softening coefficients in the presence of fibres in the concrete mix. Rather than providing a whole new equation of softening coefficient for SFRC panels; they have added an enhancement factor ($W_f$) as a multiplier to the existing softening coefficient equation:

$$W_f = 1+ 0.2 * FF \qquad \text{Eq. (2)}$$

Where

$$FF = V_f * L_f / D_f \qquad \text{Eq. (3)}$$

$V_f$ is the fiber-volume ratio
$D_f$, is the fiber diameter
$L_f$ is the fiber length

To validate the finite element model, the specimen tested by Epackachi et al. (2014) was simulated. The authors conducted an experimental study to investigate the behaviour of large-scale steel-plate composite (SC) walls subjected to displacement-controlled cyclic lateral loading representative of seismic loading. The testing program involved four rectangular SC wall specimens with an aspect ratio (height-to-length) of 1.0. The studs and tie rods are spaced at distance 102 mm and 305 mm respectively; the height, length and overall thickness of the wall is 1524mm, 1524mm and 305 mm respectively; the thickness of each faceplate is 4.8mm; the reinforcement ratio is 3.1%; the faceplate slenderness ratio is 21; and concrete strength measured on the day of the tests is 31MPa. The diameters of the studs and tie rods were 9.5 mm for all walls. The studs and tie rods were fabricated from carbon steel with nominal yield strength of 345 MPa. The yield and ultimate strengths of the steel faceplates, calculated from three coupon tests, were 262 and 380 MPa, respectively. The SC1 wall is modelled and validated against experimental results as shown in Fig. 4. It can be seen that pinching of the load deformation response as observed in experimental testing is not captured in the analytical load deformation response (Normal Concrete (NC)-Blue Colour) as the present model does not include the plate buckling and bond-slip behaviour which are primary load resisting mechanism. However, the present model can capture the peak shear strength, initial stiffness, deformation capacity, and energy dissipation with reasonable accuracy.

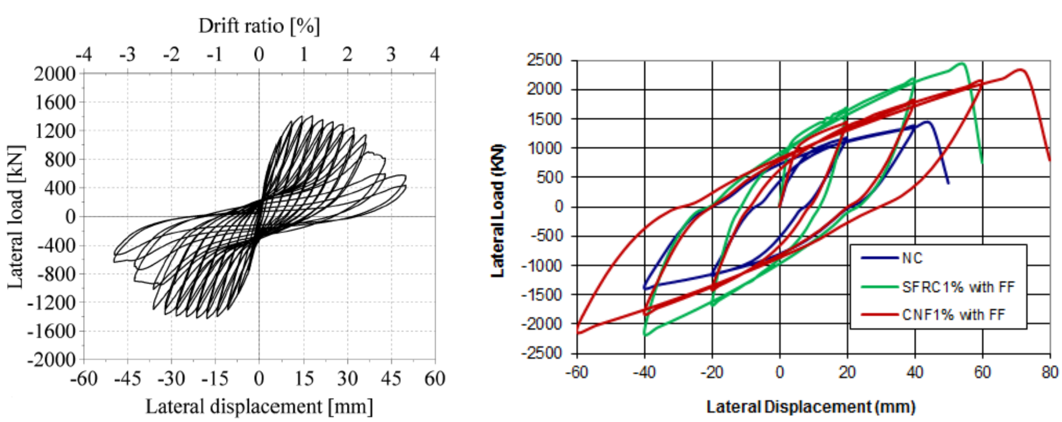


Figure 4. Load-Deflection Curve – Left: Experimental Right: Numerical. (Epackachi et al., 2004)

Henceforth, the same model has been used to investigate the effect of fibre on load-deformation characterises. The concrete compressive and tensile strength of steel fiber Vf= 1% are 40.85 MPa and 4.7 MPa respectively, (Cucchiara et al., 2004). The concrete compressive and tensile strength of carbon nano fibre Vf= 1% are 32.75 MPa and 4.48 MPa respectively, (Howser, 2010). It can be seen that SFRC 1% and CNF 1% provide better overall performance than that of NC. In addition, 1% SFRC provides higher initial stiffness and peak shear strength but less energy dissipation and deformation capacity than that of 1% CNF. The similar observation for SFRC has been reported by several researchers in case of reinforced concrete members.

Also, the experimental work of Sohel and Liew (2014) is modelled using the fibre beam element. In this impact problem, a drop-weight impact test machine was used where the drop height was fixed at 3 m and the projectile mass was 1246 kg. The SC panel slab was simply supported with a span of 1000mm. The panel had a steel plate thickness of 5.96 mm, a Lightweight concrete core of 100 mm thickness containing 1% steel fibre. The concrete density was equal to 1445 kg/m3, the cylinder strength of the concrete was 28.5 MPa, the elastic modulus of concrete was 14.0 GPa and the yield strength of steel plate was 315.0 MPa. From Fig. 5, it can be shown that the fibre beam element was able to model the SC panel subjected to the impact force with reasonable accuracy while considering the addition of the 1% steel fibre.

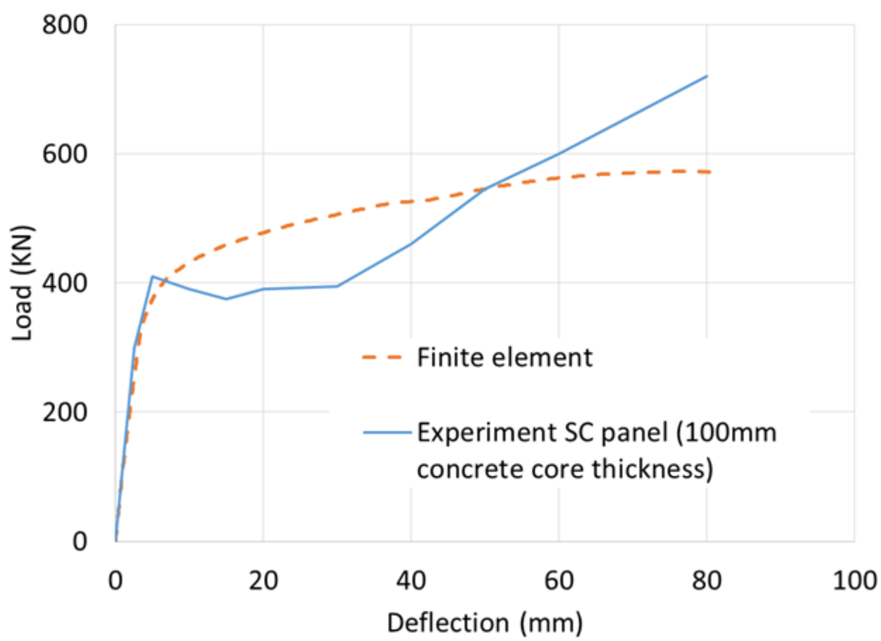


Figure 5. Load-Deflection Comparison between the Experiment Results and the Fibre Beam Element where 1% Steel Fibre is Considered (Sohel and Liew, 2014)

## BEHAVIOR OF FIBER-REINFORCED STEEL-CONCRETE SPECIMEN

In light of the results obtained from the previous section on the mechanical properties of CNFRC, this finding was noteworthy, and motivated the experimental program described here. This section reports on the experimental programme which was designed to study the performance of SC beams with different fiber reinforced concretes subjected to four-point flexural loading.

The experimental investigations in this chapter focus on the out-of-plane flexural behaviour of a typical SC wall in a structure subjected to the postulated loading. In the nuclear structure, SC walls are used in containment structures which are subjected to an internal pressure at specific sections. In marine or offshore structures also the SC walls are subjected to lateral load. As shown in Fig. 6, considering an area in the central region along the structural height, where the effects of restraint at the top and the bottom are negligible, the complete wall section can be simplified into a partial section of the wall; and a beam segment can be considered to study the behaviour of the wall. Therefore, in this research, samples were designated as a beam model. Several SC beams were designed and tested as part of this research program. The beams designed and studied in this research are considered to be a section of a wall.

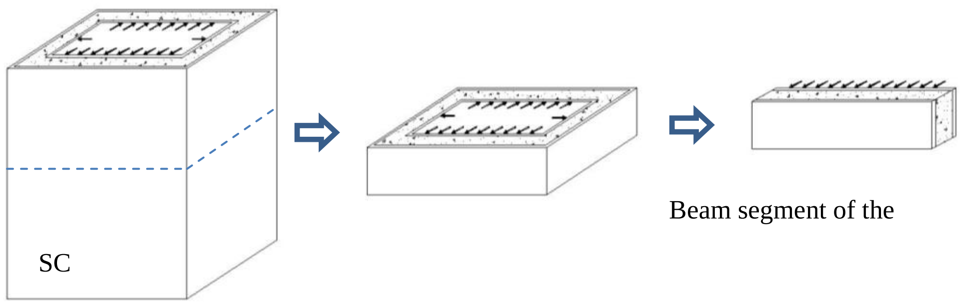


Figure 6. Schematic sketch of beam subsection taken from structural wall

The beam specimens had identical geometry while differing in the type of concrete core. The samples were constructed and tested under four-point loading. The SC sandwich beam samples used in this study consisted of two steel plates which were connected by tie bars to serve as an out of plane shear reinforcement and the plates are anchored to concrete using headed shear studs, providing composite action between concrete and steel plate. The use of tie bars connecting the plates also eases specimen handling and constructing as the beam itself acts as a mould. A schematic section of a typical SC wall is shown in Fig. 7. All beams were intended to have similar dimensions while the type of the concrete core varied for each beam to evaluate the effect of fibers on the performance of the beam.

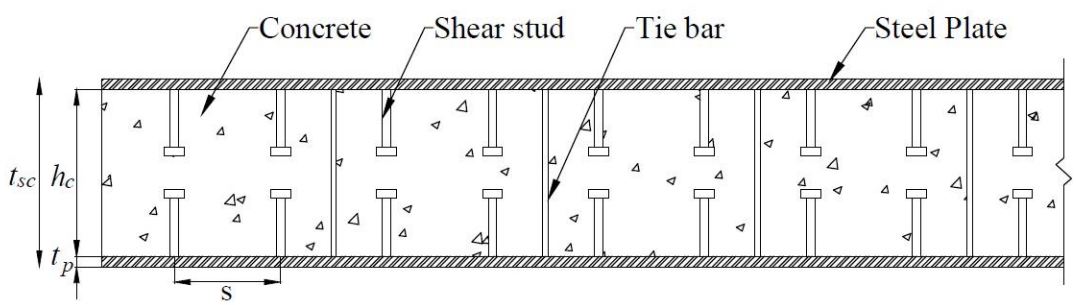


Figure 7. Schematic illustration of SC wall section

The Universal, open structure flexural frame with maximum loading capacity of 300kN from CONTROLSGROUP was used for conducting the 4-point bending test on SC beams. The beam span was 1.4 m with the shear span of 450mm and load bearing distance of 500mm (Fig. 8). Strain gauge wires were connected to channels of a data logger connected to a PC, logging the strain output automatically at every 1 second. The load was applied in a load control manner with a rate of 80 N/s up to 50kN. Afterwards, the load was applied in a displacement control manner with the rate of 2μm/s for higher precision.

The maximum load obtained from the tests along with the corresponding displacement is shown in Table 1 below. From the table, it was shown that the addition of fibers with less than 1% concentration did not affect much the results. However, when using fibers of 1.5% and 2% concentration, it was clear that both the strength and ductility were improved.


Figure 8. SC beam 4-point bending test set-up

Furthermore, the combination of macro steel fibers and nano carbon fibers proved to be an efficient method to improve the behaviour. From one end, the presence of nano fibers helped crossing the micro cracks, preventing them from initiating from the start and resulting in delayed crack formation and a better crack pattern, while the steel fibers helped crossing the macro shear crack after it formed adding more strength and ductility to the system. It appears that a total concentration of at least 1.5% fibers of both types is needed in order to accomplish the desired improvement in behaviour.

Table 1 Results of SC Beam Tests

| Concrete type | $P_{max}$ (kN) | $\Delta_{max}$ (mm) |
|---|---|---|
| PC | 169.6 | 7.6 |
| SFRC0.5 | 191.9 | 7.4 |
| CNFRC0.5 | 131.6 | 6.5 |
| CNFRC1.0 | 168.8 | 7.7 |
| SF0.5 + CNF1.0 | 230.0 | 28.4 |
| SF1.0 + CNF1.0 | 236.5 | 28.1 |

## CONCLUSION

The paper presents a research study on the use of different types of fibres to enhance the performance of steel-concrete (SC) composite elements. In particular, the paper evaluates the beneficial effects on structural behavior of newly discovered CNF, which has gained more attention in the world of nanotechnology and is being studied extensively for the past few years. However, the study on CNF concrete is limited to the material level and is mainly focused on cement mortar paste. A material test on CNF mortar has shown that the addition of such fibers increases the compressive and flexural strength of the mortar. In this study, CNF is considered in the concrete and it was evident that the addition of fibers improved the mechanical properties of the concrete. There is a gap in finding the effect of CNF concrete on the behavior of structural systems, which in this study was analysed through experiments on representative specimens and analysis using the general purpose Finite Element Programme FEAPpv. The results showed that CNF concrete enhances the behaviour of the structural members under hazard loads, as well as improve the strength, ductility and energy absorption. Locally also they are effective in improving crack patterns and resisting/delaying buckling of the faceplate. The performance of SC walls proved to be better when a hybrid CNF/steel fiber concrete is used.

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