Steel and Composite Structures, Vol. 3, No. 4 (2003) 289-306
DOI: http://dx.doi.org/10.12989/scs.2003.3.4.289

Experimental investigation of low-velocity impact characteristics of steel-concrete-steel sandwich beams

K.M.A. Sohel†, J.Y. Richard Liew‡, W.A.M. Alwis‡, and P. Paramasivam‡†

Department of Civil Engineering, National University of Singapore, BLK E1A, #07-03, 1 Engineering Drive 2, Singapore 117576

(Received April 29, 2003, Accepted July 7, 2003)

Abstract. A series of tests was conducted to study the behaviour of steel-composite sandwich beams under low velocity hard impact. Damage characteristic and performance of sandwich beams with different spacing of shear connector were evaluated under impact loading. Thin steel plates were used as top and bottom skins of the sandwich beams and plain concrete was used as the core material. Shear connectors were provided by welding of angle sections on steel plates. The sandwich beams were impacted at their midpoint by a hemispherical nose shaped projectile dropped from various heights. Strains on steel plates were measured to study the effects of impact velocity or impact momentum on the performance of sandwich beams. Spacing of shear connectors is found to have significant effects on the impact response of the beams.

Key words: experimental research; low velocity impact; sandwich composite beam; shear connector; strain time response.

1. Introduction

Steel-concrete-steel sandwich consists of a layer of plain concrete, sandwiched between two layers of relatively thin steel plates which are connected to the concrete by welded shear connectors. The performance of sandwich composite has shown its superiority over traditional composite systems in application requiring high strength, high ductility, as well as high energy absorbing capability. The apparent advantages of the system are that the external steel plates act as both primary reinforcement and permanent formwork, and also as impermeable, impact and blast resistant membranes (Roberts *et al.* 1996). The connection between the steel and concrete is in the form of mechanical shear connectors which allow the shear transfer of the forces in the concrete to the steel and vice versa, and which also prevent vertical separation of the concrete and steel components (Oehlers and Bradford 1999).

Some structures that are subjected to short-duration (dynamic) loads, typically one million times faster than the static loading case, will exhibit some changes in material response. Such structures and structural elements are required to be designed to resist dynamic as well as static loads. It is well

†Research Student
‡Associate Professor
‡†Professorial Fellow

understood that the strengths of both concrete and steel increase with increasing loading rate, and that the fracture characteristics of cementitious composites changes dramatically under dynamic loading (Mindess *et al.* 1986 & 1989). Distinct changes, when they do occur, will usually enhance the material response and failure criteria, enabling a structure to better withstand an impact loading (Bischoff and Perry 1995). Under high strain rate structures behave rather differently than they are under static loading (Holt 1994). An impact situation commonly refers to a collision of two or more objects and the event happens in such a short duration that the resulting forces and displacement are highly time dependent. Impact loading can be characterised as a kind of dynamic loads but the entire loading event happens within few milliseconds. The dynamic load due to impact is different from that due to earthquakes or wind effects.

The dynamic loading investigated in this study relates to what is commonly known as the beam impact problem (Banthia *et al.* 1987, Bentur *et al.* 1986, Mindess *et al.* 1986, Hughes and Beeby 1982). The impact is caused by a mass (the projectile) falling on a single-span sandwich beam which is initially at rest. The force transmitted to the beam by the projectile depends on the mass, shape and the impact velocity of the projectile as well as the mass, stiffness, and the mechanical properties of the beams. Considering all these factors, a full description of an impact problem is rather complex. The objective of the present research is to study the impact behaviour of steel-concrete-steel sandwich beams with middle core made of concrete. High Strength concrete was chosen as the first alternative to a normal concrete sandwich filler core. This is because high strain rates appear to have a less profound effect on the stress strain relationship of high strength concrete than on low or moderate strength concrete (Bing *et al.* 2000). Effect of concrete core is investigated by providing one layer of wire mesh in view of its enhanced fracture toughness (Khan 2000).

Research on steel-concrete-steel sandwich beams and panels under static loading have been investigated by Roberts *et al.* (1996), Oduyemi and Wright (1989), Write *et al.* (1991), Tomlinson *et al.* (1989), and Simon *et al.* (2003). However, research information related to impact behaviour of composite sandwich is very limited. Instrumented impact testing (Aymerich *et al.* 1996, Banthia *et al.* 1987 & 1989, Bentur *et al.* 1986, Mindess *et al.* 1987 & 1986, Ong *et al.* 1999) gives a deeper understanding of the impact process and provides quantitative data that may be helpful in design. In this present investigation, quantitative and qualitative study of the effects of low velocity hard impact on steel-concrete-steel sandwich beams was performed using an instrumented drop-weight impact test facility developed at the structural Engineering Laboratory of NUS. Destructive and nondestructive test methods are then applied to quantify the impact damage. A variety of impact-related parameters that are found to be related to the impact velocity is studied.

2. Experimental programme

2.1. Test Specimens

Tests were carried out on forty-five steel-concrete-steel sandwich specimens with dimension of 100 mm (width) × 50 mm (thickness) × 1200 mm (length). Thin steel plates of 5 mm thick were used as top and bottom skins of the sandwich beams. Either plain concrete or wire mesh reinforced concrete was used as the core material. Shear connectors were provided by welding of equal angle sections with dimension of 25 mm (leg) × 3 mm (thickness) × 100 mm (length) on the steel plates. According to shear connector spacing, the beams were categorised into five types. The spacing of shear connector was varied as 150 mm, 200 mm, 240 mm, 300 mm and no shear connector. No major reinforcement bar was

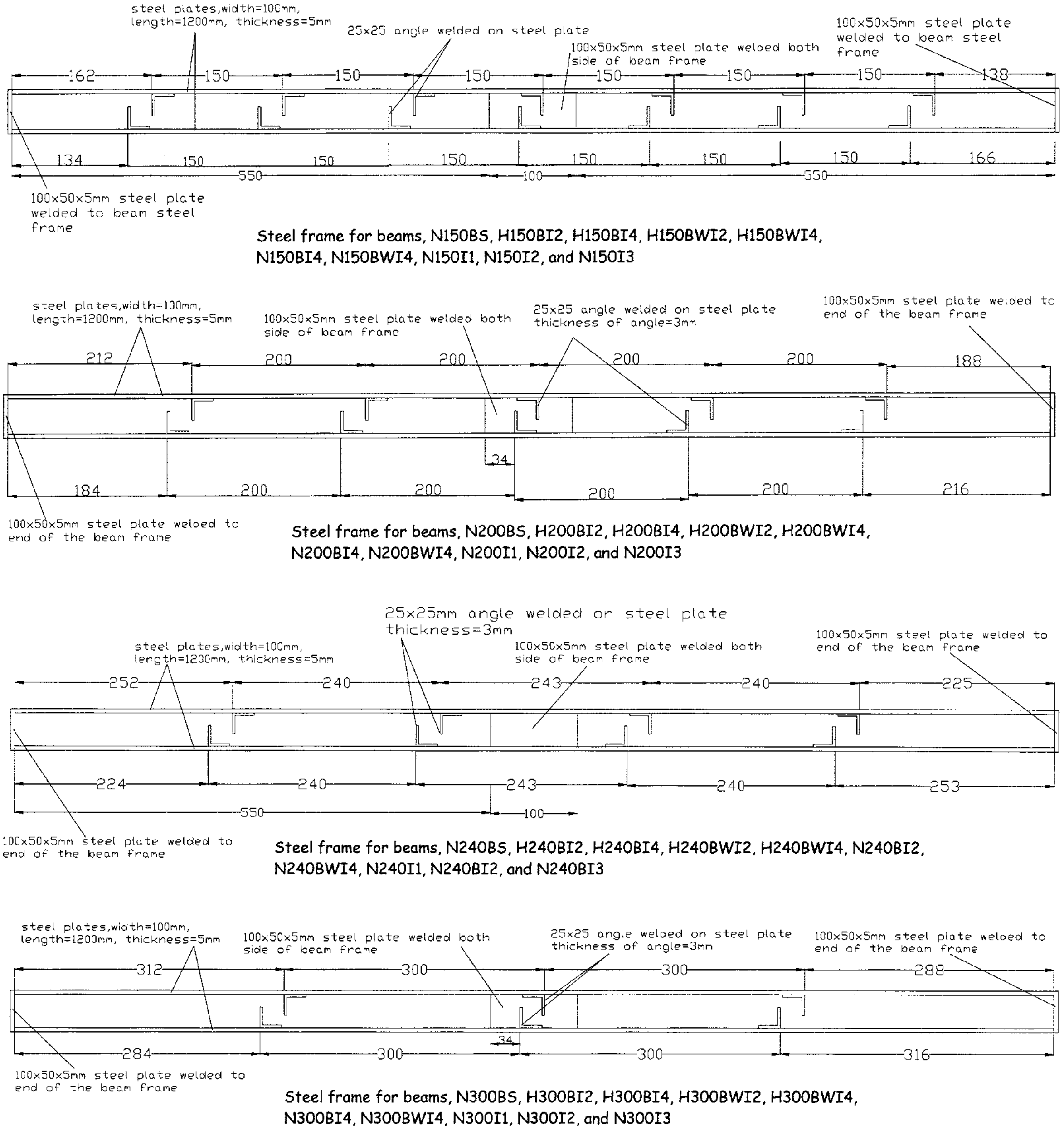


Fig. 1 Details sandwich beam specimen

provided in the sandwich core, which enabled the performance of shear connectors to be studied exclusively. The details of all the test specimens are shown in Fig. 1.

For convenience, the specimens were tested in two phases. In the first Phase, thirty specimens were tested under impact loading. Ten of them were subjected to impact by dropping the projectile (43 kg mass) from 1.5 m which produced an impact velocity 4.66 m/s. The remaining twenty specimens were subjected to a dropping weight (31 kg mass) from 3.5 m which produced an impact velocity of 6.50 m/s.

Table 1 Details of test specimens

Beam designation	Concrete strength (N/mm^2)	Shear connector spacing (mm)	Beam designation	Concrete strength (N/mm^2)	Shear connector spacing (mm)
Phase I tests					
Plain concrete			Concrete with one layer of wire mesh		
Projectile mass = 43 kg, drop height = 1.5 m			Projectile mass = 43 kg, drop height = 1.5 m		
H150BI2	96.13	150	H150BWI2	93.03	150
H200BI2		200	H200BWI2		200
H240BI2		240	H240BWI2		240
H300BI2		300	H300BWI2		300
H00BI2		Nil	H00BWI2		Nil
Projectile mass = 31 kg, drop height = 3.5 m			Projectile mass = 31 kg, drop height = 3.5 m		
H150BI4	101.50	150	H150BWI4	97.76	150
H200BI4		200	H200BWI4		200
H240BI4		240	H240BWI4		240
H300BI4		300	H300BWI4		300
H00BI4		Nil	HBWI4		Nil
Projectile mass = 31 kg, drop height = 3.5 m			Projectile mass = 31 kg, drop height = 3.5 m		
N150BI4	57.44	150	N150BWI4	59.03	150
N200BI4		200	N200BWI4		200
N240BI4		240	N240BWI4		240
N300BI4		300	N300BWI4		300
N00BI4		Nil	N00BWI4		Nil
Phase II Tests					
Plain concrete					
Projectile mass = 43 kg, drop height = 1 m					
N150I1	73.55	150			
N200I1		200			
N240I1		240			
N300I1		300			
N00I1		Nil			
Projectile mass = 43 kg & drop height = 2 m					
N150I2	74.19	150			
N200I2		200			
N240I2		240			
N300I2		300			
N00I2		Nil			
Projectile mass = 43 kg & drop height = 3 m					
N150I3	73.76	150			
N200I3		200			
N240I3		240			
N300I3		300			
N00I3		Nil			

Table 2 Mixture compositions of concrete

Material	Normal concrete (kg/m^3)	High strength concrete (kg/m^3)
Portland cement	350	500
Sand (< 5 mm)	650	650
Sand (<0.4 mm)	-	-
Aggregate (<10 mm)	1250	1120
Silica Fume	-	60
Superplasticiser	2	20
Water	165	134

Some of the beam specimens contained a layer of wire mesh with an aim to improve the fracture toughness of the concrete core.

In the second phase of the tests, fifteen specimens were tested under impact loading with different velocities of the projectile. Five of them were tested under projectile velocity of 4.18 m/s which was produced by dropping the projectile from 1 meter height. Five of them were tested under projectile velocities of 5.90 m/s by dropping the same projectile from 2 meter. The remaining five beams were tested under projectile velocity of 7.23 m/s by dropping it from 3-meter height. The span dimensions and overall thickness were kept identical as those of the first phase. Specimen details for phases I and II tests are summarised in Table 1. The specimen attributes in Phase I tests such as H150BI2 or H200BWI4 are explained as follow. (H) and (N) denoted specimens with high strength or normal strength concrete; (B) and (BW) denoted specimens without and with a layer of wire mesh. The number after (H) is the spacing of shear connector in mm. (I) indicates impact and the number followed is the drop height in m. For Phase II tests, N150I2 represents normal strength concrete specimen with shear connector spacing of 150 mm subject to impact with a drop height of 2 m.

2.2. Material

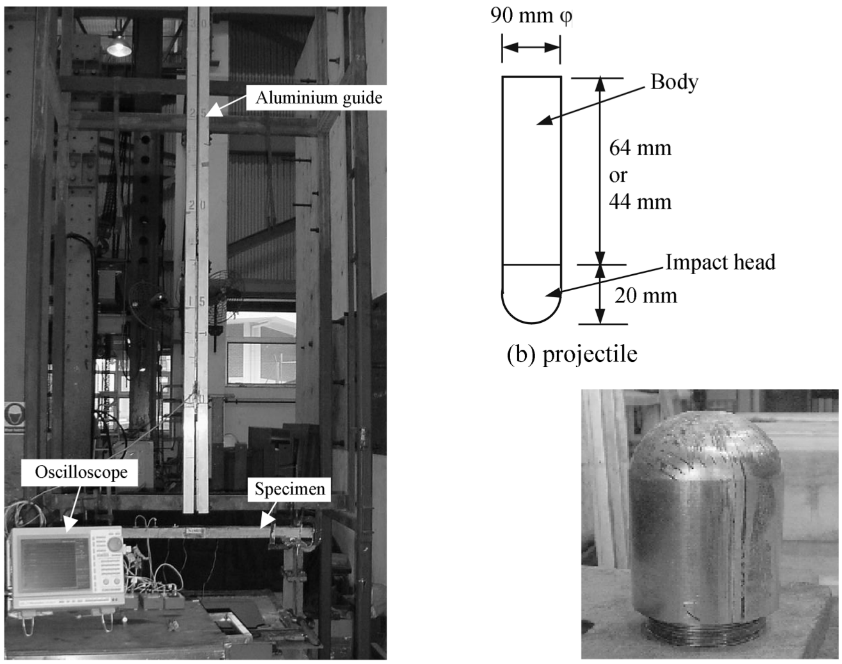
Tensile coupon tests were conducted on the 5 mm steel plates and the angle shear connectors. The average yield strength of steel plate was 324.9 N/mm^2 and the yield strength of the angles was 344.8 N/mm^2.

The concrete used for the sandwich beams consisted of Ordinary Portland Cement, sea dredged sand and a crushed stone coarse aggregate of 10 mm maximum size. The mix proportions used for sandwich beams are presented in Table 2. The average compressive strength of the concrete obtained from cube tests are given in Table 1.

For some specimens in the phase I tests, one layer of wire mesh was placed 5 mm below the top steel plate. The wire diameter was 1.42 mm, and the spacing in both directions was 12.5 mm.

2.3. Test set-up

An instrumented drop weight impact machine, similar to that described by Ong *et al.* (1999), was used for impact testing. The test set-up used is shown in Fig. 2. The specimen was supported on two rollers on a heavy frame of the test rig with a clear span of 1000 mm between two roller supports. A central impact was achieved by means of a guide rail which was fabricated using aluminium angles. The projectile was allowed to slide freely up and down in the guide which was supported by a self-supporting steel frame (Fig. 2a). The projectile could be raised up to a maximum height of 4.5 meter by



(a) Full view of experimental set-up for impact loading

(b) projectile

(c) impact head

Fig. 2 (a) Full view of experimental set-up for impact loading (b) projectile and (c) impact head

a hand winch through a high-tension steel wire. The projectile was dropped from a desired height, guided by the aluminium guide rail, onto the test specimen to generate an impact load on the specimen. Grease was applied to reduce the friction along the guides and to ensure a controlled and smooth fall. In order to achieve different impact momentum, the projectile mass was varied from 31 to 43 kg and a range of drop heights varying from 1 to 3.5 meter was utilized. The tip of the projectile had a diameter of 90 mm (Figs. 2b, 2c).

2.4. Instrumentation

A schematic diagram of the instrumentation and data acquisition system is presented in Fig. 3. The impact head of the projectile was instrumented with a set of strain gauges to measure the impact load. Strain gauges attached to the beam were used to measure the strain response of the steel skin of the beam. A digital circuit in combination with laser emitters and photodiodes were used to determine the incident velocity of the projectile. When the projectile crosses the first photodiode, the data acquisition system was triggered and the data captured over a specified interval. The instrument outputs were recorded using a sixteen-channel oscilloscope which was set at a scanning rate of 1 MHz per channel. A pre-trigger interval was also specified so that no data were lost as acquisition of data proceeds.

The contact force was obtained using the following expression,

$$F(t) = \varepsilon(t) \cdot E \cdot \frac{\pi D^2}{4} \tag{1}$$

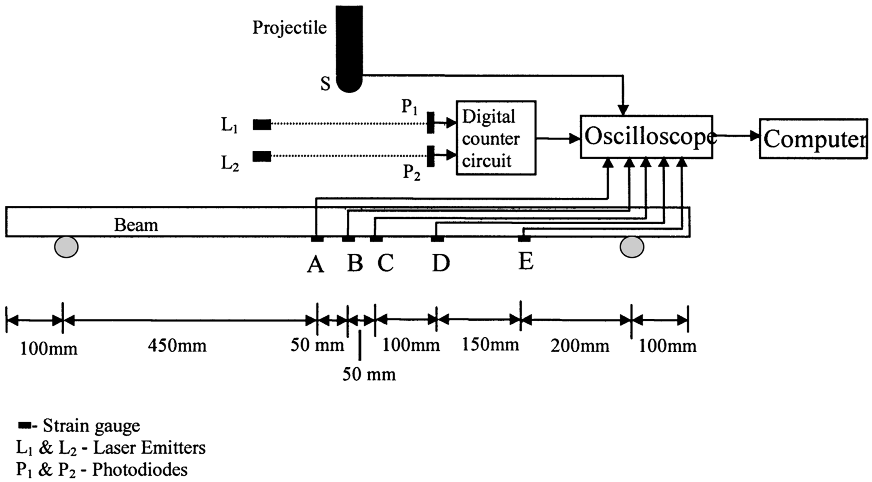


Fig. 3 Schematic diagram of instrumentation and data acquisition system

where $\varepsilon(t)$, E and D are the strain at the impact head of the projectile at time t, modulus of elasticity of the projectile material and diameter of the projectile head respectively.

The impact incident velocity was measured using the following expression,

$$v = \frac{d}{t} \tag{2}$$

where d and t are the distance between the laser emitters and time taken to pass this distance by the projectile.

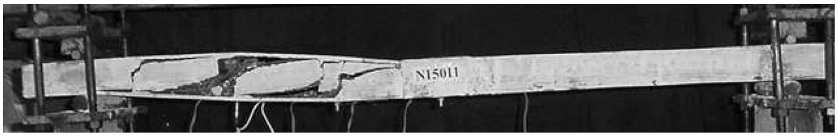
The impact incident velocity (v) of the projectile multiplied by the mass (m) of the projectile gives the applied momentum (mv). After the impact, the steel plate's separations were measured. The residual deflections at center of the beams were also measured using the floor as reference for all specimens tested.

3. Test results & observations

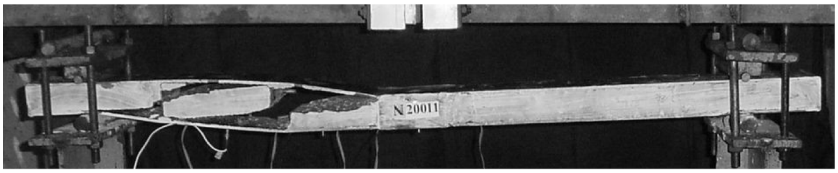
3.1. Impact damage behaviour

The failure of the sandwich beams under impact was dreadful as seen in Figs. 4-7. The projectile did not fracture the beams completely. It was observed from the experiments that when the projectile struck the beam, very high stresses developed in the vicinity of impact point. When the stresses flowed towards the supports, separation of steel plates occurred and the concrete core cracked into pieces at locations away from the impact point. The beam, upon impact, gained momentum and underwent large displacements. The steel skins were separated and vertical cracks occurred in the concrete core.

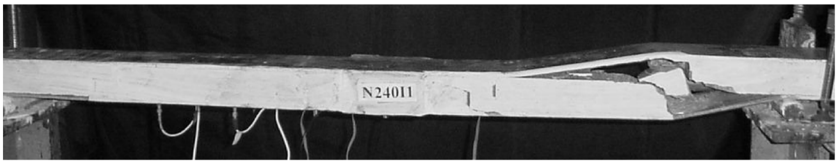
Upon impact, stress wave tends to transmit from steel to concrete core through shear connector, and high stress concentration occurs at the shear connector position. This caused the cracking of concrete at the connector position and led to the separation of steel plates. Beams with 150 mm spacing of shear connector showed relatively small separation of steel plates, whereas, beams with wider spacing of



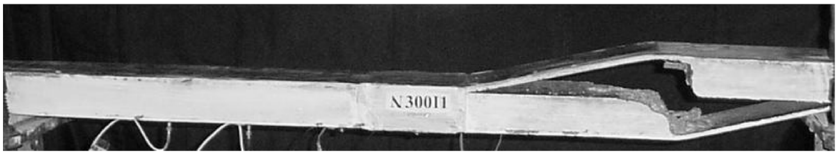
(a) N150I1



(b) N200I1

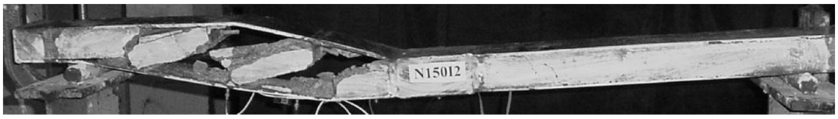


(c) N240I1

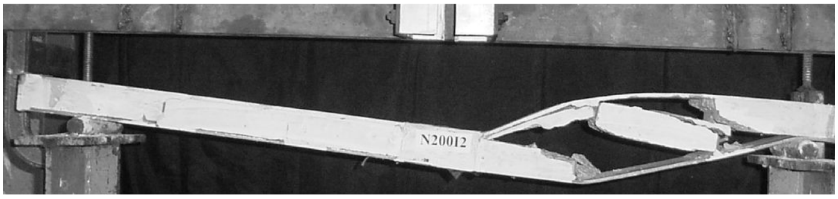


(d) N300I1

Fig. 4 Failure pattern of beams under impact loading with drop height 1 meter; (a) N150I1 (b) N200I1 (c) N240I1 (d) N300I1



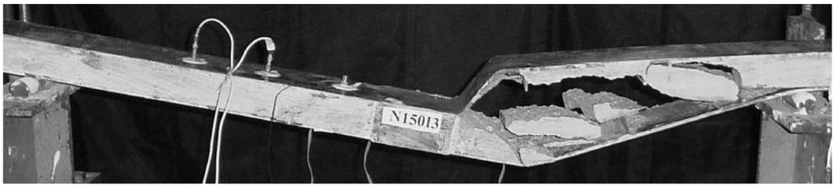
(a) N150I2



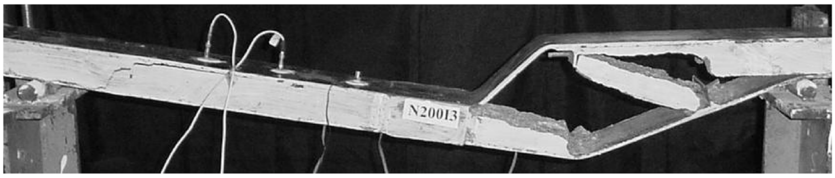
(b) N200I2

Fig. 5 Failure pattern of beams under impact loading with drop height 2 meter; (a) N150I2 (b) N200I2

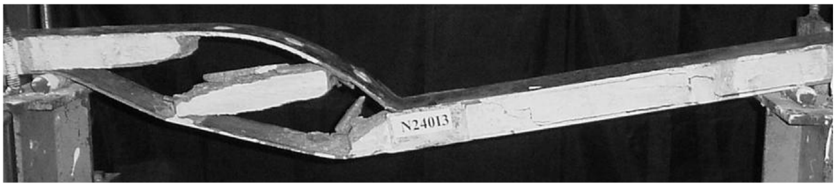
shear connector (200 mm, 240 mm, and 300 mm) showed higher separation of steel plates. This phenomenon can be observed from the crack patterns of specimens with different spacing of shear connectors, as shown in Fig. 4. Beams with one layer of wire mesh experience smaller separation of steel plates than that without wire mesh (see Fig. 7). This is because the wire mesh holds the concrete together and prevents spalling of the concrete. Fig. 8 shows that the separations of steel plates are wider with an increase in impact momentum.



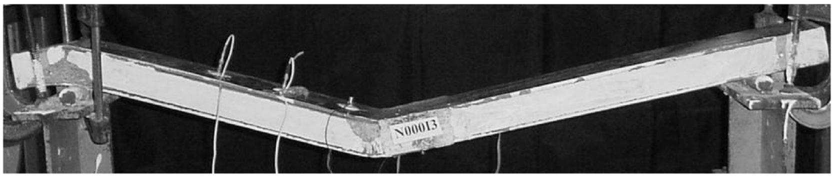
(a) N150I3



(b) N200I3



(c) N240I3



(d) N000I3

Fig 6 Failure pattern of beams under impact load with drop height 3 meter; (a) N150I3 (b) N200I3 (c) N240I3 (d) N000I3.

(a) Beam with one layer of wire mesh and shear connector spacing of 200mm

(b) Beam with plain concrete and shear connector spacing of 200mm

Fig. 7 Comparing the damage between beams with wire mesh and without wire mesh

Upon impact, the beam experienced a sudden displacement at the load point. A portion of this displacement recovered as soon as the impact load disappears. The residual deflections at the beams center were measured. The measured values of residual deflection are presented in Tables 3 and 4. The residual deflections of the beams center after impact with projectile momentum of 316.8 kg.m/s were

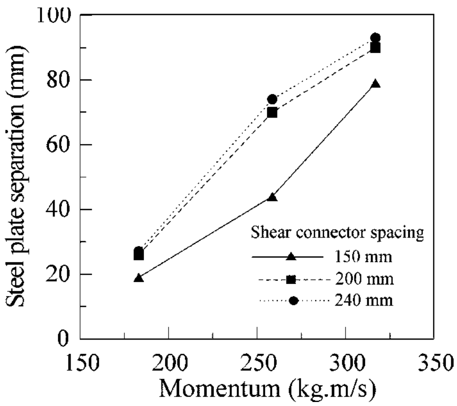


Fig. 8 Effect of impact momentum on steel plate separation (projectile mass 43 kg)

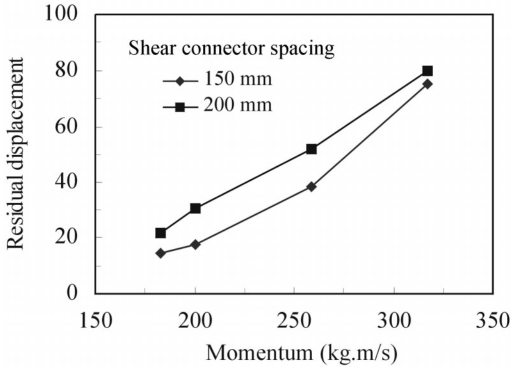


Fig. 9 Effect of momentum on residual displacement of sandwich beams (projectile mass 43 kg)

Table 3 Effect of shear connector on residual displacement

Shear connector spacing	Impact momentum (kg-m/s)			
	183.2	200.7	258.5	316.8
	Residual displacement (mm)			
150 mm	14.2	17.5	38.9	69.9
200 mm	21.6	30.7	52.3	79.8
240 mm	22.1	36.2	N.A.	87.2
300 mm	23.7	N.A.	N.A.	N.A.
No shear connector	23.9	68.3	N.A.	95.1

Table 4 Effect of wire mesh on residual displacement after impact

Impact momentum 200.7 kg-m/s		
Shear connector spacing	Residual displacement (mm)	Residual displacement (beam with wire mesh) (mm)
150 mm	17.5	15.3
200 mm	30.7	26.0
240 mm	36.2	N.A.
300 mm	N.A	44.2
No shear connector	68.3	53.6

69.9 mm, 79.8 mm, 87.2 mm and 95.1 mm for the beams with shear connector spacing 150 mm, 200 mm, 240 mm and no shear connector respectively. This reflects the increase in stiffness and the decrease in the degree of damage experienced by the beam with closer connector spacing. Specimens with wire mesh reinforcement exhibit an improved performance in stiffness and integrity after impact. From Table 4, it is evident that the residual deflection significantly decreased by providing a layer of wire mesh in the concrete core. Fig. 9 shows that the residual deflection increases with an increase in impact incident velocity, i.e., with an increase in impact momentum. The rate of increase in residual deflection increases with the projectile velocity. This implies that the beam experienced more plastic deformation

Table 5 Steel plate separation of sandwich beams after impact

Projectile mass 43 kg			Projectile mass 31 kg		
Beam ref.	Impact velocity (m/s)	Steel plates separation (mm)	Beam ref.	Impact velocity (m/s)	Steel plates separation (mm)
H150BI2	4.66	15	H150BI4	6.50	72
H200BI2	4.66	45	H200BI4	6.50	74
H240BI2	4.66	52	H240BI4	6.50	65
H150BWI2	4.66	24	H240BWI4	6.50	49
H200BWI2	4.66	33	N150BI4	6.50	65
H300BWI2	4.66	87	N240BI4	6.50	74
N150I1	4.18	19	N300BI4	6.50	75
N200I1	4.18	26	N150BWI4	6.50	65
N240I1	4.18	27	N200BWI4	6.50	59
N300I1	4.18	49	N300BWI4	6.50	115
N150I2	5.90	44			
N200I2	5.90	70			
N150I3	7.23	79			
N200I3	7.23	70			
N240I3	7.23	73			

with higher impact momentum.

Fig. 6(d) shows the failure pattern of beam without shear connector under impact with drop height of 3 meter. Steel plate separation did not occur for the beams without shear connector. But their residual deflections were higher than beams with shear connectors (see Tables 3 and 4). Residual deflection of the beam with 150 mm spacing of shear connector was 17.5 mm at impact momentum 200.7 kg.m/s whereas, the residual deflection of the beam without shear connector was 68.3 mm at the same impact momentum. This translates into an effective increase in stiffness upon impact damage of the beams with the addition of shear connector.

3.2. Load-time history

Fig. 10 shows the impact force-time history of beams with different spacing of shear connector. Upon impact, the beam experienced a sudden increase in impact force which rises to the maximum value in 500 μs. The time to reach peak impact force was very short because of the hard contacts between the steel projectile and the steel plate (Hughes and Speirs 1983). The multiple contacts between the beam and the projectile were characterised by the occurrence of multiple peaks, referred as secondary peaks, as shown in the observed load-time curves in Figs 10 and 11. The peak loads may be influenced by various parameters. However, in the present study, the nose shape of the projectile, beam thickness and the boundary conditions were kept the same and hence, the peak load was affected mainly by the drop height of the projectile, type of concrete core used and the shear connector spacing in the specimen.

From the impact force-time history (Fig. 10) of the beams tested by dropping the projectile from 1 meter height, it may be seen that the beam with 150 mm spacing of shear connector resisted higher impact force than other beams with wider spacing of shear connector. The peak impact force was increased about 13% when shear connector spacing changed from 200 mm to 150 mm. This observation is

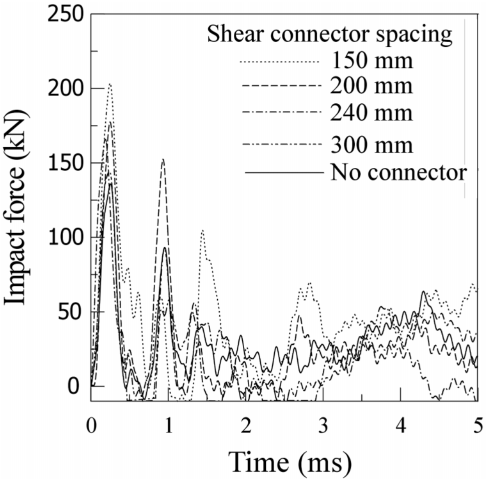


Fig. 10 Effect of shear connector spacing (impact momentum 183.2 kg.m/s)

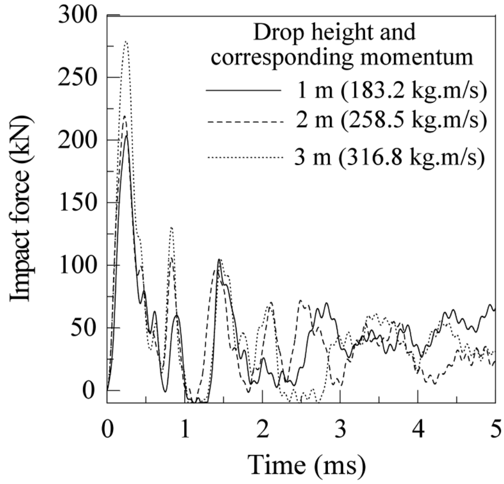


Fig. 11 Impact force time history of beams with different drop height (connector spacing 150 mm)

also true for beams tested by dropping the projectile from 2 meter and 3 meter height (see Fig. 12). From Fig. 12, it may be seen that the impact force on the beams with 150 mm spacing of shear connector are always higher than the beams with 200 mm spacing of shear connector for the same impact momentum. This is because closer spacing of shear connector increases the composite action between steel and concrete and also increases the stiffness. However, the difference reduces at high impact momentum region (> 300 kg.m/s).

Fig. 11 compares the impact force-time histories of beams with 150 mm spacing of shear connector subjected to impact loads with various drop heights. The peak impact forces were increased by about

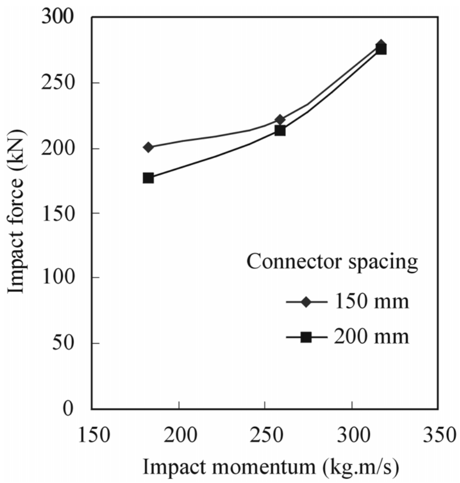


Fig. 12 Effect of impact momentum on impact force of sandwich beams.

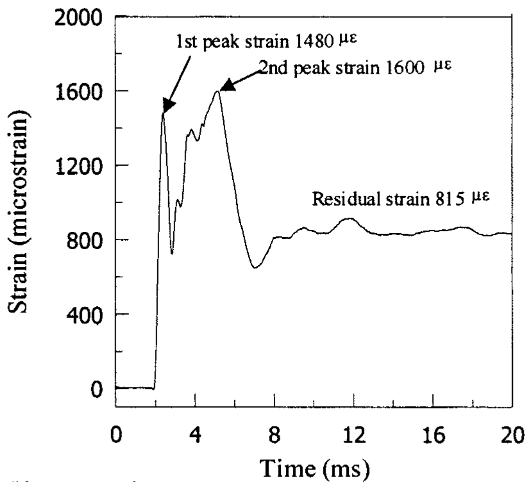


Fig. 13 Strain response of bottom steel plate at midpoint of sandwich specimen N150I3 with impact momentum 316.8 kg.m/s

11% and 39% when the projectile velocity increased from 4.18 m/s to 5.90 m/s and 7.23 m/s, respectively. Fig. 12 shows the variation of the peak impact forces with the impact momentum for the beams with 150 mm and 200 mm spacing of shear connector. It is observed that the peak impact forces on the beams increase with an increase in the impact incident velocity of the projectile i.e. with an increase in the impact momentum. The ultimate impact capacity of the beams cannot be determined from the tests, because the beam did not fracture completely after impact although the concrete core crushed and cracked into pieces. Instead, the impact strength of the beam can be assessed based on limiting damage experienced by the beams.

3.3. Strain history

Strain gauges were placed on the bottom surface of the steel plate of the beam as shown in Fig. 3 to measure the strain-time history during impact. Typical strain time curves are plotted in Figs. 13-15. Multiple peak strains were observed and finally a permanent residual strain was recorded. Values of the maximum and residual strains are presented in Table 6.

Figs. 16 and 17 show the strain-time histories for specimens with various spacing of shear connectors. It was generally observed that the first peak strain of the bottom steel plate (directly across the impact location) decreased with the increase in number of shear connectors, i.e., with closer spacing of shear connector. The residual strain also increased with the wider spacing of shear connector. Larger residual strains on the steel plates indicate the severity of the damage, which increases with the spacing of the shear connectors. Spacing of shear connector also affects on the time difference between the 1^{st} and 2^{nd} peak strains. Generally beams with 150 mm spacing connector took 0.35 to 0.45 ms to reach 1^{st} peak whereas beams with 200 mm spacing connector took 0.60 to 1.09 ms. This trend is also seen for other beams with wider spacing of shear connector.

The strain recovery was calculated as the difference between the peak strains and the residual strains. The recovery percentage is the difference with respect to the peak strain. The recovery from this peak strain was significantly higher for beams with closer shear connector. It was generally observed that the beams with 150 mm spacing of shear connector recovered 52% to 76% of their first peak strain before

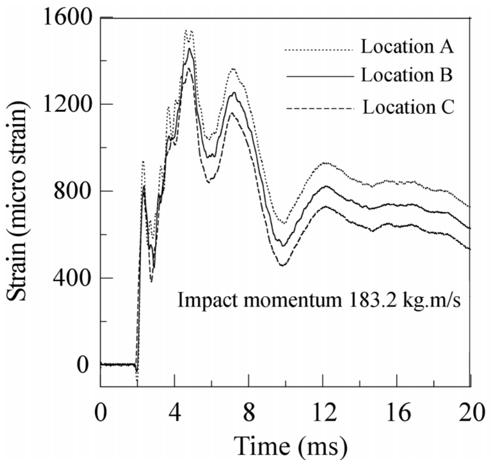


Fig. 14 Strain response of sandwich specimens N150I1 under impact

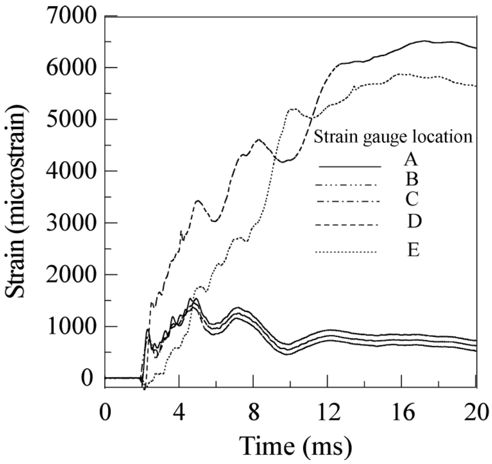


Fig. 15 Strain time response of bottom steel plate of beam N150I1 under impact momentum 183.2 kg.m/s

Table 6 Peak strain and strain recovery

Beam ref.	Impact Velocity (m/s)	Central strain (με)		Residual Strain (με)	% Recovery	
		1st peak	2nd peak		1st peak	2nd peak
Projectile mass = 43 kg						
H150BI2	4.66	1269.97	1475.99	300.00	76.38	79.67
H200BI2	4.66	979.96	1117.17	466.91	52.35	58.21
H240BI2	4.66	1673.07	1678.09	716.00	57.20	57.33
H300BI2	4.66	1144.55	1144.55	268.52	76.54	76.54
H00BI2	4.66	783.20	1199.84	470.36	39.94	60.80
H150BWI2	4.66	941.21	1426.15	450.38	52.15	68.42
H200BWI2	4.66	895.01	1506.78	481.49	46.20	68.05
H240BWI2	4.66	1269.97	1475.99	286.58	77.43	80.58
H300BWI2	4.66	1125.95	1222.15	486.84	56.76	60.17
H00BWI2	4.66	630.37	1218.58	317.89	49.57	73.91
H200BI4	6.50	1599.44	1610.81	679.84	57.50	57.80
N150I1	4.18	798.05	1364.33	522.01	34.59	61.74
N200I1	4.18	812.81	1046.90	543.45	33.14	48.09
N150I2	5.90	1161.62	1709.15	510.35	56.07	70.14
N200I2	5.90	1133.56	1561.19	841.31	25.78	46.11
N150I3	7.23	1479.44	1599.96	829.48	43.93	48.16
N200I3	7.23	1434.96	1966.58	979.98	31.71	50.17
Projectile mass = 31 kg						
H150BI4	6.50	1333.73	1548.17	412.91	69.04	73.33
H200BI4	6.50	1373.21	1397.40	633.24	53.89	54.68
H240BI4	6.50	2126.01	1387.87	423.00	80.10	69.52
H150BWI4	6.50	1598.67	1633.61	479.23	70.02	70.66
H240BWI4	6.50	1911.36	1874.23	343.68	82.02	81.66
H300BWI4	6.50	1767.47	1693.32	485.42	72.54	71.33
N150BI4	6.50	1796.54	1807.25	581.72	67.62	67.81
N200BI4	6.50	1864.71	1838.34	598.23	67.92	67.46
N240BI4	6.50	2008.42	1876.15	940.40	53.18	49.88
N300BI4	6.50	1392.33	1392.33	366.66	73.67	73.67
N00BI4	6.50	1443.27	1615.78	1186.80	17.77	26.55
N150BWI4	6.50	1424.32	1330.37	339.03	76.20	74.52
N200BWI4	6.50	1483.92	1574.33	407.88	72.51	74.09
N240BWI4	6.50	2272.29	1715.76	552.29	75.69	67.81
N300BWI4	6.50	1392.39	1392.39	390.41	71.96	71.96
N00BWI4	6.50	1463.04	1804.07	896.51	38.72	50.31

settling at a residual strain whereas the beams without shear connector recovered 17.7% to 49.6% of their peak strains (see Table 6). This trend also observed for the second peak strains. This behavior implies that the beams without shear connector experience more internal damage and deflection after impact than beams with shear connectors. As expected specimens with high strength concrete generally recorded smaller steel strains than specimen with normal strength concrete. The first and the second

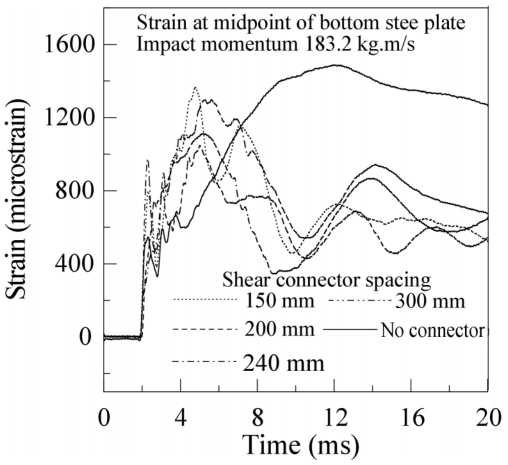


Fig. 16 Effect of shear connector spacing; strain time history (projectile mass 43 kg)

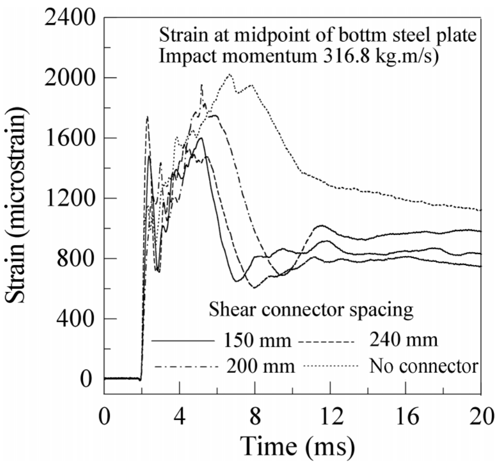


Fig. 17 Effect of shear connector spacing; strain time history (projectile mass 43 kg)

peak of bottom strains for the beam H150BI4 (see Table 6) were 1650.65 $\mu\varepsilon$ and 1676.73 $\mu\varepsilon$ respectively, while these for the beam N150BI4 were 1796.54 $\mu\varepsilon$ and 1807.25 $\mu\varepsilon$ respectively; the increments were 9% and 8% respectively.

3.4. Effect of wire mesh in concrete on strain-time response

From the strain time plot shown in Fig. 18, it may be concluded that the presence of a layer of wire mesh in the concrete helps to reduce the peak strain in the bottom steel plate. It is seen from this figure that the first and the second peak strains were reduced by about 24% and 12% respectively. Residual stain was also reduced by about 40%. In most cases, residual strains for the beams with one layer of wire mesh were lower than those for the beams without wire mesh (see Table 6).

3.5. Effect of impact velocity on strain-time response

Fig. 19 shows the strain-time histories for specimens with different drop height of the projectile. The peak strains and the residual strains increase with increase in the drop height of the projectile, i.e., increase in the impact momentum. Table 6 shows that the first peak strain was increased by about 39% and 85% when the projectile velocity was increased from 4.18 m/s to 5.90 m/s and 7.23 m/s, respectively. Same phenomenon was also observed for the second peak. The residual strain was increased by about 55% and 80% when the projectile velocity increased from 4.18 m/s to 5.90 m/s and 7.23 m/s respectively.

3.6. Effect of projectile mass on impact

Twenty-five beam specimens were tested with projectile mass 43 kg with different impact velocities and twenty specimens were tested with projectile mass 31 kg with impact velocity of 6.5 m/s. From Table 6, it may be seen that the projectile mass has an influence on strain-time response of steel plates. It is generally observed that for the approximately same momentum but different mass and velocity, the

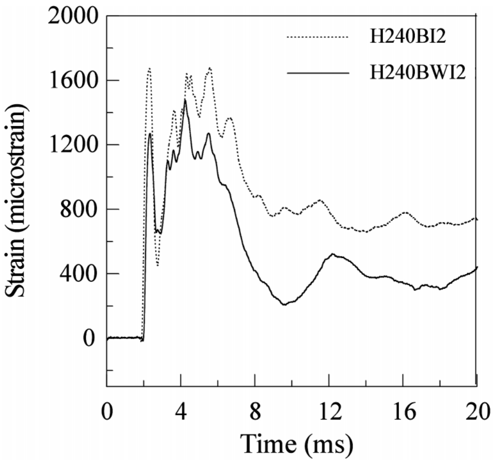


Fig. 18 Effect of wire mesh on strain at mid point of bottom steel plate upon impact (impact momentum 200.7 kg.m/s)

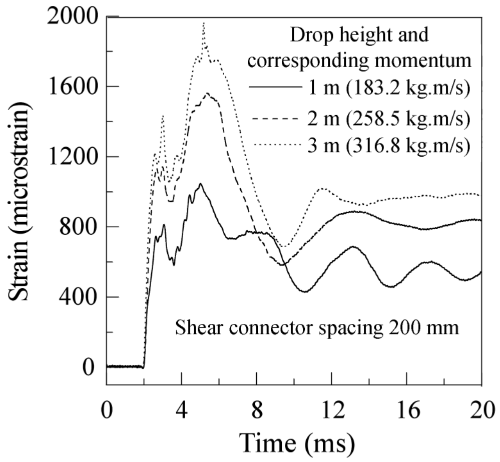


Fig. 19 Strain-time history of beams with different drop height (projectile mass 43 kg)

strain responses were different. For example, beam H150BI2 was impacted by 200.7 kg.m/s momentum and beam H150BI4 by 201.5 kg.m/s momentum, but their 1st peak strains were 1269.97 $\mu\varepsilon$ and 1333.73 $\mu\varepsilon$ respectively. The residual strains were 300 $\mu\varepsilon$ and 412.91 $\mu\varepsilon$, respectively. The same phenomenon was also seen for the steel plate separation (see Table 5) and for the residual displacement. This implies the strain rate sensitivity of the beam materials.

3.7. Assessment of impact damage

From the impact momentum, residual displacement relationship and the steel plate separation of the damaged specimens, it is possible to develop an idea to quantify the damage incurred due to the impact. For the beam with shear connector 150 mm and without wire mesh, significant damage occurs when the impact momentum is equal or higher than 183.2 kg.m/s. To minimize damage (the residual displacement and steel plate separation) due to impact, the impact momentum should be kept at below 183.2 kg.m/s. Similarly, for beam with 150 mm spacing of shear connector and with one layer of wire mesh, considerable damage occurred at 200.7 kg.m/s of impact momentum with residual displacement and steel plate separation of 15.3 mm and 24 mm, respectively.

Beams with wider spacing of shear connector also developed substantial damages at 183.2 kg.m/s of impact momentum. Damages are characterised by a higher level of residual displacement, larger steel plate separation and higher residual strain in steel plate would indicate significant internal damage.

Due to stress concentration, cracks initiate at shear connector position and led to steel plate separation by buckling of steel pate. The angle connector provides lateral resistant to prevent buckling of the steel plate under compression. However, when cracking of concrete occurs at the connector location, the connector was detached from the concrete and the resistance to the plate is lost. This increases the buckling length and the plate is more susceptible to buckling. From the observed failure mode of the sandwich beams, it can be inferred that the shear connectors which connect both steel plates should be used in shallow depth sandwich structures to minimize the steel plate separation.

4. Conclusions

This paper investigates the behaviour of steel-concrete-steel sandwich beams subjected to low velocity hard impact. The following conclusions were drawn from the experimental study conducted on forty-five sandwich beam specimens.

1. Beams with one layer of wire mesh on the concrete core performed better in terms of impact resistance, as they registered less damage and residual strain than the beams without wire mesh due to the increase of toughness and integrity of concrete.
2. Shear connectors are effective not only in transferring the horizontal shear but also in improving the stiffness of beams. The test specimens clearly show an increase in impact force when closer shear connector spacing is used.
3. The rate of fracture energy absorption was very high during the initial period of the impact. Beam with closer shear connector spacing tends to absorb more energy because of the increase in stiffness. The additional of a layer of wire mesh in the concrete core significantly improved the energy absorption of the sandwich beams compared to that of without the wire mesh.
4. Impact velocity of the projectile has great influence on the impact force, strain of steel plate, residual deflection and plate separation. These values go up with the increase of impact velocity.
5. Damage (steel plate separation) of beams upon impact increases with wider spacing of shear connector. However, the beams without shear connector did not show any separation but their permanent deflections were higher than that of beams with shear connectors.
6. Upon impact, strains of steel plates reached multiple peak values and then recover and stabilize at a permanent residual strain. It was generally observed that upon impact the peak strain and residual strain of the bottom steel plate decreased with the increase of number of shear connectors due to the increase of interaction between steel plates and concrete.

The experimental programme presented in this paper provides an insight into the impact performance of sandwich beams. The sandwich composite system is suited to extensive fabrication to site delivery and the concrete within the steel plates is of structural significant to resist impact load.

References

Aymerich, F., Marcialis, P., Meili, S., Priolo, P. (1996), “An instrumented drop-weight machine for low velocity impact testing”, *Proc. of the Fourth Int. Conf. on Structures Under Shock and Impact IV,* Udine, Italy, July, 243-253.

Banthia, N.P., Mindess, S., and Bentur, A. (1987), “Impact behaviour of concrete beams”, *Materials and Structures*, **20**, 293-302.

Banthia, N.P., Mindess, S., Bentur, A., and Pigeon, M. (1989), “Impact testing of concrete using a drop-weight impact machine”, *Experimental Mechanics*, **29**, 63-69.

Bentur, A., Mindess, S. and Banthia, N.P. (1986), “The behaviour under impact loading: Experimental procedure”, *Materials and Structures*, **19**, 371-378.

Bing, L., Park, R, Tanaka, H. (2000), “Constitutive behavior of high strength concrete under dynamic loads”, *ACI Struct. J.*, **97**(4), 619 629.

Bischoff, P.H., Perry, S.H. (1995), “Impact behavior of plain concrete loaded in uniaxial compression”, *J. of Eng. Mech.*, ASCE, **l21**(6), 685-693.

Holt, P. J. (1994), “A procedure for assessment of steel structures subject to impact or impulsive loading”, *Proc. of the Third Int. Conf. on Structures under Shock and Impact III*, Madrid, Spain, June, 157-164.

Hughes, G., and Beeby, A.W. (1982), “Investigation of the effect of impact loading on concrete beams”, *The*

Structural Engineer, **60B**(3), 45-52.

Khan, M.A.K.B. (2000), "Impact behavior of fibre reinforced cementitious composite slabs", Ph.D. Thesis, National University of Singapore, Singapore.

Mindess, S., Banthia, N.P., and Bentur, A. (1986), "The response of reinforced concrete beams with fiber concrete matrix to impact loading", *The Int. J. of Cement Composites and Lightweight Concrete*, **8**, 165-170.

Mindess, S., Bentur, A., Yan, C. and Vondran, G. (1989), "Impact resistance of concrete containing both conventional steel reinforced and fibrillated polypropylene fibers", *ACI Materials Journal*, **86**(6), 545-549.

Oduyemi, T.O.S. and Wright, H.D. (1989), "An experimental investigation into the behavior of double-skin sandwich beams", *J. of Constructional Steel Research*, **14**(3), 197-220.

Oehlers, D.J., Bradford, M.A. (1999), *Elementary Behaviour of Composite Steel and Concrete Structural Members,* Butterworth-Heinemann publishing Inc. Oxford, Boston.

Ong K.C.G., Basheerkhan, M., Paramasivam, P., (1999), "Resistance of fibre concrete slabs to low velocity projectile impact", *Cement & Concrete Composites*, **21**(5-6), 391-401.

Roberts, T.M., Edwards, D.N., Narayanan, R. (1996), "Testing and analysis of steel - concrete - steel sandwich beams", *J. of Constructional Steel Research*, **38**(3), 257-279.

Simon K. Clubley, Stuart S.J. Moy, Robert Y. Xiao (2003), "Shear strength of steel - concrete - steel composite panels. Part I - testing and numerical modelling", *J. of Constructional Steel Research*, **59**, 781-794.

Tomlinson, M., Chapman, M., Wright, H.D. (1989), "Tomlinson, A. & Jefferson, A. Shell composite construction for shallow draft immersed tube tunnels", *ICE Int. Conf. on Immersed Tube Tunnel Techniques*, Manchester, UK, April.

Wright, H.D., Oduyemi, T.O.S and Evans, H.R. (1991), "The design of double skin composite elements", *J. of Constructional Steel Research*, **19**(2), 111-132.

Wright, H.D., Oduyemi, T.O.S. and Evans, H.R. (1991), "The experimental behavior of double skin composite elements", *J. of Constructional Steel Research*, **19**(2), 97-110.

SC