

SHEAR BEHAVIOR OF REINFORCED CONCRETE BEAMS WITH CONFINEMENT NEAR PLASTIC HINGES

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1 INTRODUCTION

From observation of plastic hinge formation, the beam hinge concept has now become fairly standard. This requires more attention to reinforcement detailing [1]. The intention is that once plastic hinges form in the beams adjacent to the column, they will be subjected to severe cracking and damage during an earthquake. The question then arises whether the damaged hinge zone will retain enough shear strength to hold up the beams and the floors after the earthquake. The end hinge zones, having been bent well into the failure region both ways, will be cracked right through top to bottom, and concrete may well have spalled away from both faces when under compression. Also the rebars may well have buckled top and bottom. So it seems likely that the shear strength will have been greatly reduced. Binding of the compression zone, or of entire columns, is of course fairly common already in seismic design of concrete structures. Often spirals of steel, even interlocking spirals, are used. The question addressed here is whether such spirals are useful to carry shear in beams, and in particular whether they can usefully improve the residual shear strength at hinges after severe cyclic bending.

2 EXPERIMENTAL STUDY

The experimental program is divided into two stages. The first stage consists of static shear tests for simply supported beams. The second stage, cyclic testing, is applied to beams which have similar configuration to the ones tested in stage one. The test program was designed to examine the effectiveness of spirals as lateral reinforcement. The beams were identical except for the transverse reinforcement provided. Two types of lateral reinforcement were used; spirals fabricated from 2.5mm plain mild round steel bars with yield strength of 700 MPa, and normal closed rectangular stirrups with yield strength of 450 MPa (for more details see Fig. 1 and Table 2).

2.1 Experimental Aims

Experiments in stage one were done to test the behaviour of spirals when subjected to static shear and to quantify their amount of shear contribution in different geometrical configurations (Fig. 1). It was also aimed to investigate the validity of using a simplified sectional crack analysis in assessing the shear behaviour in the conducted experiments. This is particularly relevant for beams reinforced with double and single spirals where tie action cannot easily form a simple truss system. Experiments in the second stage aimed to study the effect of spiral confinement in maintaining the residual shear strength by preventing the concrete from spalling and the steel from buckling. The test series is divided into different sets where each set is made up of different number of beams. The beams have different transverse reinforcement configurations as shown in Table 2.

2.2 Design of stage-one experiments

A total of 20 concrete beams were included in the investigation of stage one and two (only relevant results are given in this paper). All the beams reported in table 2 for stage two had an overall length of 2500mm, an effective span of 2200mm and a shear span to depth ratio $a/d = 5$ when tested under cyclic loading and 2.3 when tested under subsequent shear. The beams were cycled through a fixed sequence of mid span displacement, and the required maximum force was measured.

Conventionally reinforced beams (i.e. beams with normal links) were designed for shear according to BS 8110. Beams with spiral reinforcement were designed using sectional analysis where an imaginary cracking plane at failure is assumed. Their shear capacity is obtained by alteration of the average integration method proposed by Presitley [2] using a discrete computation method to calculate the induced error that results from by neglecting the force variation along the circular shape

of the spiral and assuming it to be constant [3]. The error is then added to the integrated method to come up with a factored equation for the spiral shear resistance. Hence spirals in these cases are assumed to contribute to the overall shear resistance by the self anchored force that will develop in the spirals as cracks cross them.

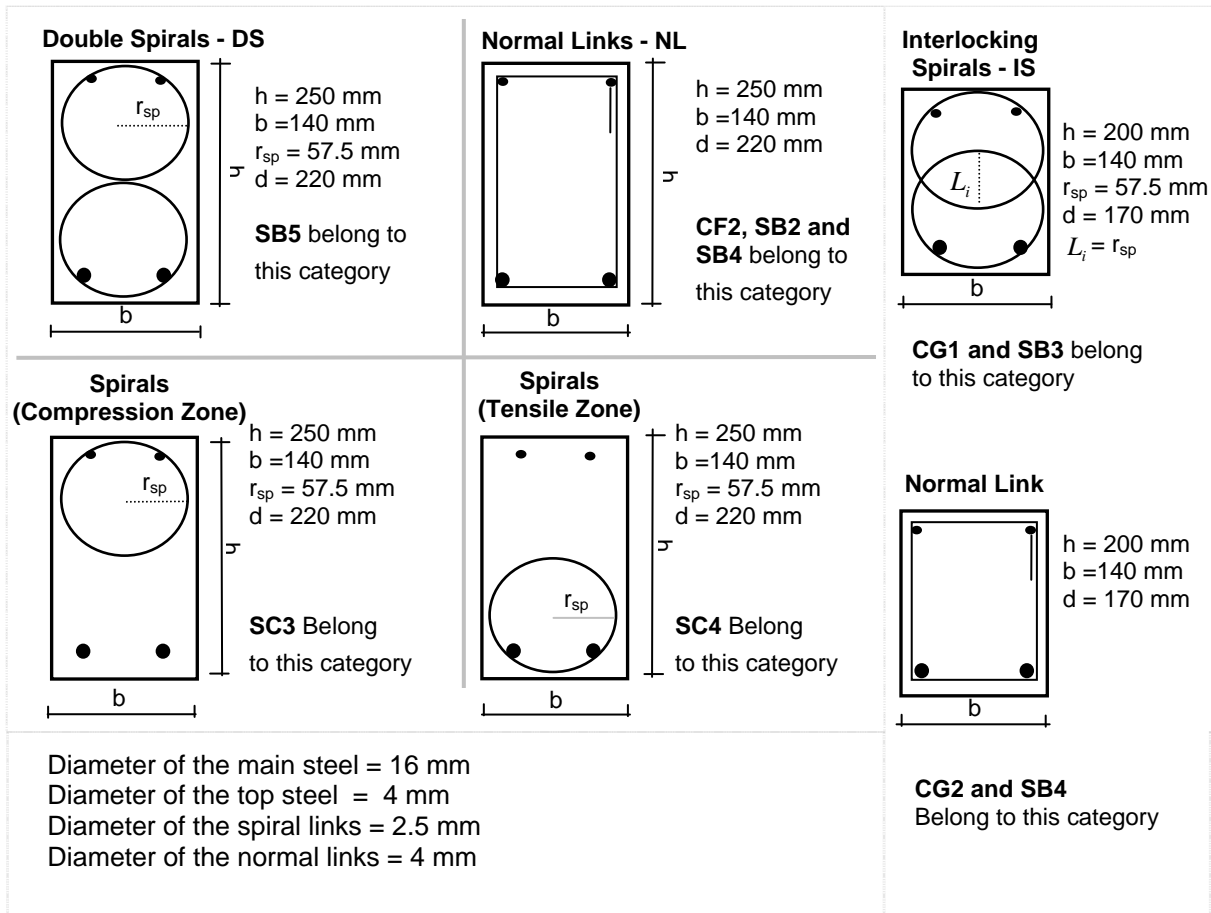


Fig. 1 Cross section through typical beams

In designing the shear strength of SB2, SC3 and SC4, discrete crack-section analysis was also used, but the assumed cracking plane crosses the spirals in only one zone (either compression or tension). Hence spirals in these cases are assumed to contribute to the overall shear resistance by the self anchored force that will develop in the spirals as cracks cross them.

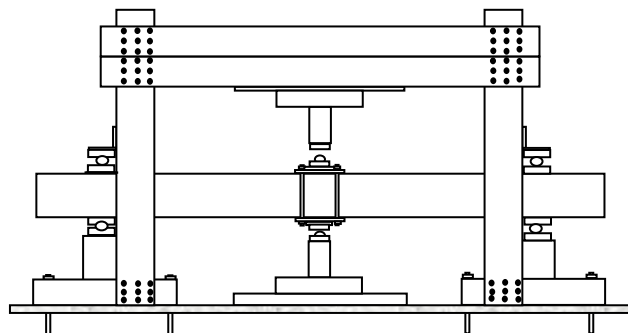


Fig. 2 Schematic view of the test rig

All the beams in the two stages were tested under a point load. To prevent anchorage failure of the longitudinal bars, the beams were extended beyond the supports and the bars on the tension face of the beams were bent through an angle of 90° for a distance at least 150mm. A schematic drawing for the test rig used to test beams in both stages is shown in Fig. 2 At the end of the cyclic sequence, the

supports were moved so that the same a/d ratio was attained as for the static tests in stage one. Static load was then applied, controlling the load not displacement, until a shear failure occurred.

3 STAGE ONE RESULTS

Beams in Series C in stage one had only the compression or the tension zone reinforced with spirals, and was expected as Code prediction to have the same load carrying capacity as those without stirrups i.e. beam SD1. However their load carrying capacity exceeded that of SD1 by about 35%. In both cases, the extra shear load could not have been carried by a truss structure of the simple form usually assumed. The crack patterns present in SC3 and SC4 were comparable to those obtained in SD1 in terms of both extensiveness and character. Beam SC3 and SC4 contained a major diagonal crack, similar to the one found in type SD1, which was prevented from splitting concrete in either the compression or the tension zone by presence of transverse reinforcement. This allowed SC3 and SC4 to attain a higher shear capacity as a result of the spirals' shear contribution.

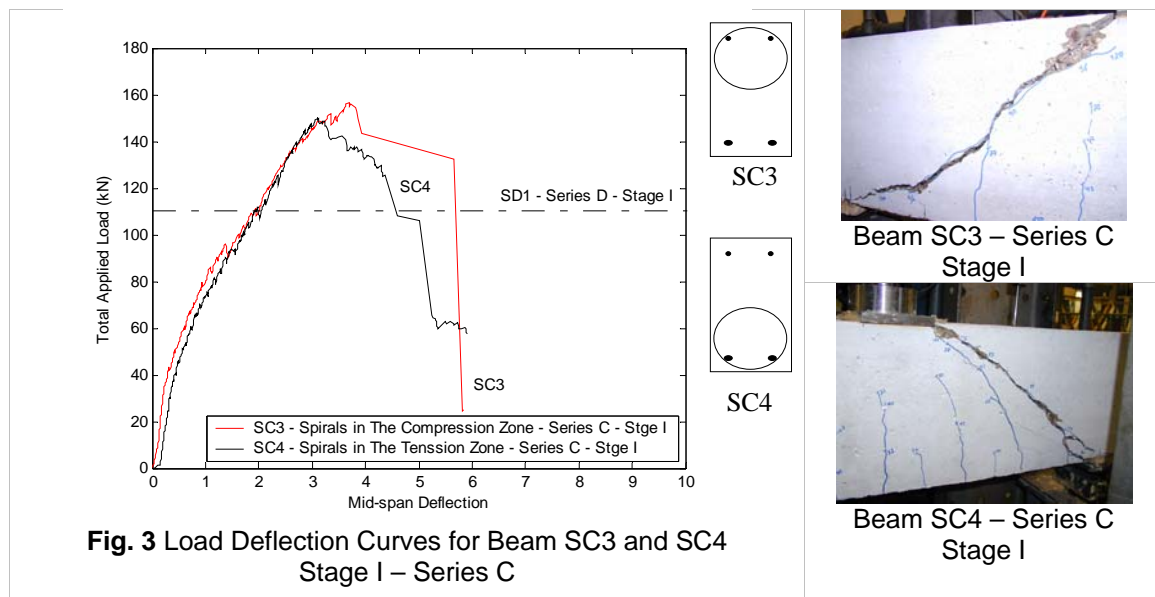


Fig. 3 Load Deflection Curves for Beam SC3 and SC4 Stage I – Series C

According to the B.S code, the behaviour of SC3 and SC4 should be similar to that of SD1 since the requirements for a full depth truss to form are not fulfilled. Thus the code neglects the effect of having spirals either in the compression or tension zone and provides a lower bound estimate for beams that have similar configuration to SC3 and SC4. Yet, to describe the significant increase in the shear carrying capacity of SC3 and SC4, one has to attribute that either to the spiral enhancement of concrete shear contribution or to the formation of tension forces within the spirals contributing to V_s .

3.1 First possibility (Enhancement of concrete shear contribution)

For concrete to carry an extra shear load, its compressive strength should be enhanced so that both its tensile and shear strength will improve accordingly. But the increase in shear capacity of SC3 and SC4 cannot be attributed in this case to the concrete shear improvement alone. Experiments confirmed that confining the concrete with similar spiral configuration, as beam SC3, did not alter the concrete strength significantly as much as it altered the strain capacity (Fig.4). Hence, the possibility that the extra shear load was carried by concrete itself should be ruled out. SC4 (with tension zone spirals only) was able to attain a shear load similar to SC3 (with compression zone spirals only) confirming that confinement is not the explanation for the shear enhancement.

Both Kotsovos [5] and Atallah [6] did similar experiments to beam SC4, not using spirals, but closed rectangular links. They attributed the enhancement that accrued in the beam capacity to the confinement, evidently neglecting the contribution that may have occurred due to a crack crossing the confinement links. Our results suggest that compression-zone confinement did not have a major effect on the shear capacity.

The presence of spirals enhances the tensile capacity of concrete. Fig.5 shows an increase in both the tensile strength and strain of a concrete splitting cylinder reinforced with spiral links. Results indicate that higher fracture energy is required for a crack to open and volume dilation to accrue. The

spirals get activated once concrete tensile capacity is exceeded. Hence spiral activation can take place in two ways, either due to concrete volume dilatation (case of compression failure) or due to cracks that crosses spiral links. Concrete crushing was not present in series C (Fig.3), hence the possibility of volume dilatation should not be considered as it was more likely that spirals were activated due to cracks (shear cracks) crossing them.

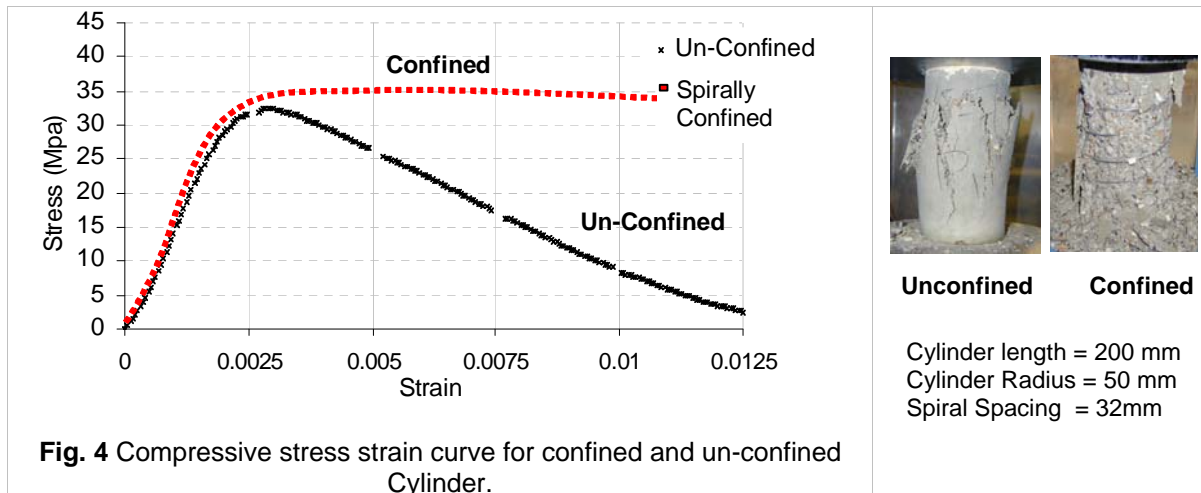


Fig. 4 Compressive stress strain curve for confined and un-confined Cylinder.

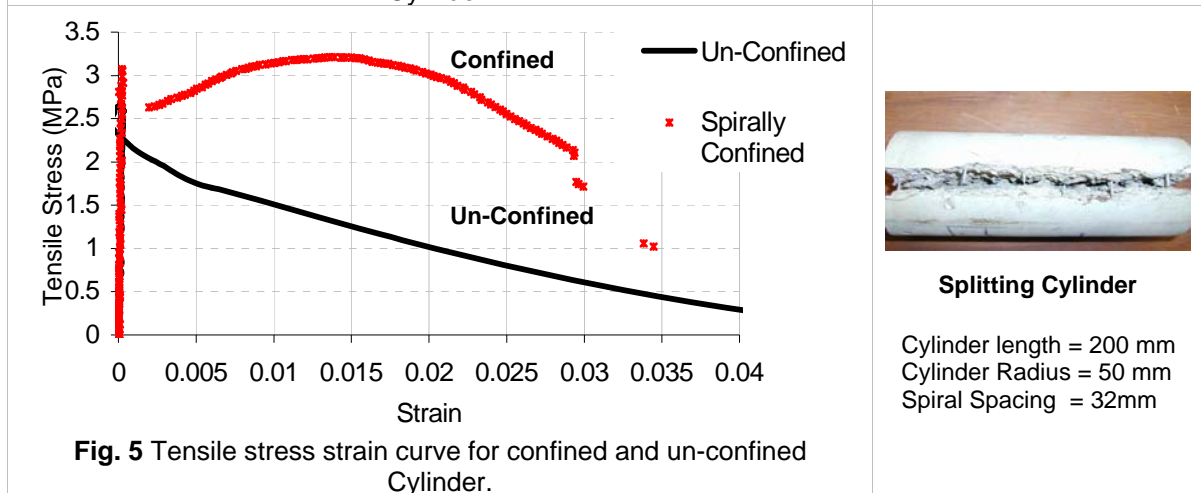


Fig. 5 Tensile stress strain curve for confined and un-confined Cylinder.

3.2 Second possibility (Spirals tension contributing to V_s)

If concrete confinement by the spirals does not have a significant contribution to enhancing the compression zone shear capacity, equilibrium in SC3 and SC4 can only be maintained if tension forces are developed in the spirals. This is possible since spirals will be self anchored due to their geometrical shape and hence any crack crossing them will be resisted by tension forces that develop in them.

The idea of tension forces forming in either the upper zone or the lower zone of the concrete beam depending on the presence of the spiral links raises many important questions about the theory of truss analogy that is based on continuity of tie action and describes how shear is resisted in reinforced concrete beams. Kotsovos in his book about ultimate limit state design of concrete structures stated that it is not a necessary condition for beams at the ultimate limit state to behave as a truss in order to resist the action of shear force. A deeper investigation of equilibrium at ULS may therefore be required.

4 STAGE TWO RESULTS

4.1 Double spirals versus normal links

Beams with spiral links (CF1 and CG1) performed beyond expectations; at the end of the cyclic test little crumbling had occurred in the plastic hinge region. There were several large flexural cracks present, which opened and closed at each cycle, but these cracks remained almost vertical.

Fig.8 demonstrates the deterioration state that the beams reached by the end of cyclic loading. The residual shear capacities of the beams were undoubtedly enhanced by the remaining presence of concrete. The presence of the spirals in the compression zones enhanced the concrete capacity under cyclic loading by preventing it from excessive volume dilation and spalling away.

The compression zone for beams with normal links (CF2 and CG2) started to degrade half way through the cyclic loading. The degradation is a result of concrete crushing and steel buckling in the compression zone. Some cycles after the deepening and connection of the cracks, a longitudinal bar in the upper zone buckled and this area of loose concrete then underwent a rapid crumbling deterioration.

In all the tested beams, the concrete started to spoil after the 4th cycle, yet in case of beams with spiral links, crushing was limited to concrete cover while the core of their compression zone was not affected. Fig. 8 shows the reduction in strength and stiffness for the tested beams. According to Fig. 8, CF2 had rapid strength deterioration after the 3rd cycle, while beams with spiral links were capable of maintaining a significant amount of their strength at higher number of cycles and larger deflections. The degradation in strength affected adversely the shear performance of the tested beams (i.e. beams with normal links). Such type of shear degradation can be attributed to the loss in concrete contribution to the shear strength and the deterioration state that the beam reached by the end of the cyclic loading.

4.1.1 Shear Test

The residual shear strength of the cycled beams was compared to the static shear strength of similar beams tested in stage one under the same geometric and testing configurations. Fig. 9 shows the shear load test comparison for the cycled and the reference beams. Beams with spiral links were capable of preserving the concrete shear contribution, and hence attaining residual shear load almost equal to their original shear capacity. The slight amount of strength and stiffness reductions in the spiral beams did not affect the beam shear performance when tested.

On the other hand, strength deterioration of normal beams seemed to have a direct effect on their shear strength. Even though fewer number of cycles and lower amount of deflections were applied (table 3), yet when tested later under shear their performance was poorer than that of spirally reinforced beams. According to figure 9, the loss in their shear strength is almost 60% in some cases, indicating that if further cycles had been applied, the beams could have failed during the cyclic loading process.

4.2 Interlocking spirals versus normal links

Figures 10 and 11 show the mid span deflections for repeated cyclic loading for CG1 and CG2. Even though, in this series the displacement ductility factor for CG1 was higher than for CG2 as shown in table 4, yet the strength degradation of the latter was much higher and its shear strength experienced a 50% reduction. Beam with interlocking spirals, CG1, did not show any strength degradation even at a displacement ductility factor $\cong 8$ which is approximately double of that of CG2 (table 4).

4.2.1 Shear test

The shear test applied for CG1 (Fig. 13) showed a ductile mode of failure, indicating the ductile state that the beam had reached during the cyclic loading without experiencing any post ductility degradation. The outcome of this tested series can be summarized as, for interlocking spirals in contrast to normal links

- During cyclic loading, the only apparent damage was in the cover of the compression zone
- The beam was capable of attaining the same shear load as that of similar beam tested under a static shear load (Fig. 13).

The experimental results obtained in this experimental study agree with those obtained by Trim [3] and Priestley. The results confirm that using spirals both as shear reinforcement and as hinge confiner improves the ductility of the plastic hinge and its residual shear performance.

5 CONCLUSIONS

Spirals are known to be very good in confining the concrete in the compression zone [4]; hence their use might be of great benefit in situations where energy dissipation is very important [5]. They will only be useful where their confinement effect is beneficial. This can be foreseen in case of earthquakes, where soft structures are subjected to cracking that creates alternating compressive

forces. This paper presented experiments on the effect of having spiral links instead of normal shear links near potential hinges. The outcome of this study can be summarized as follows:

- Beams with only spirals in the compression or in the tension zone had a good shear performance indicating that tension forces can form inside the spirals because of their self-anchorage mechanism.
- The use of “spirals” changes the performance of a plastic hinge by providing a better support that delays the onset of buckling of main bars.
- Cracks seem to be terminated by hoops and stopped from spreading.
- Given close windings, any crumbled material is also contained and shear capacity will remain even with further deterioration.
- Interlocking spirals (and to a lesser extent, double spirals) showed a better performance under cyclic loading due to confinement action and shear contribution.
- Beams with spiral shear reinforcement were capable of maintaining almost full residual shear strength.
- To avoid steel congestion and make an economic use of transverse reinforcement, spirals are suggested to act both as confining enabler in earthquake and shear resister in static loading.

ACKNOWLEDGEMENTS

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Table 1 Residual shear strength in the tested beams

Beam ID	CF1	CF2	CG1	CG2
Number of Cycles	8	5	8	6
Max Displacement Ductility Factor $\mu \cong$	+4	+4	+8	+5
Max. Mid - Span Deflection (mm)	42.74	43.17	81.29	51.27
Strength Reduction Before Shear Test %	30%	47%	7%	50%
Shear Reduction %	18%	60%	2%	62%

Table 2. Tested beam details

Stage Reference	Stage one (Static shear test)										Stage two (Cyclic and Static shear test)			
	Series B					Series C		Series D			Series F		Series G	
Series Reference	SB2	SB3	SB4	SB5	SB5	SC3	SC4	SD1	CF1	CF2	CG1	CG2		
Beam ID														
Width (mm)	140	140	140	140	140	140	140	140	140	140	140	140		
Height (mm)	250	200	200	250	200	200	200	250	250	250	200	200		
Effective Depth (mm)	220	170	170	220	170	170	170	220	220	220	170	170		
Links or Spiral spacing	110	65	110	32	65	110	110	-----	22*	110	44*	110		
Span to Depth ratio (Static)	2.27	2.94	2.94	2.27	2.3	2.3	2.3	2.27	2.27	2.27	2.94	2.94		
Span To Depth Ratio (Cyclic)									5	5	6.48	6.48		
Concrete Cube Strength (MPa)	38.2	39.5	38.2	41.4	40	38	38	43.1	41.06	38.42	41.06	38.42		
Transverse Steel Yield Strength	400	700	400	700	700	450	450	-----	480	400	480	400		
Longitudinal Steel Yield Strength	500	500	500	500	IS	NL	NL	500	500	500	500	500		
Longitudinal Steel Ratio x (10 ⁻³)	1.3	1.7	1.7	1.3	128	128	128	1.3	6.6	6.6	1.3	1.3		
Type of Shear Links	NL	IS	NL	DS	650	650	650	PL	DS	NL	IS	NL		
Useful tips	NL: Normal Links IS: Interlocking Spirals DS: Double Spirals PL: Plain Beam <ul style="list-style-type: none"> • spiral spacing was reduced to compensate for the reduction in the wire strength • Stage I is used as a reference stage for the shear design of stage II and also for comparison purpose 													

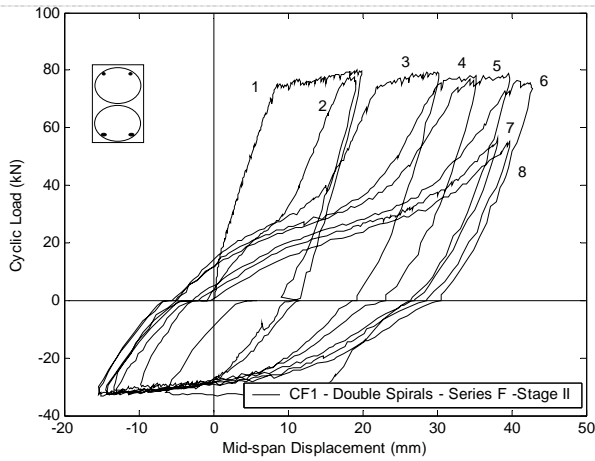


Fig. 6 Cyclic Load Deflection Curve for CF1 (Double Spirals)

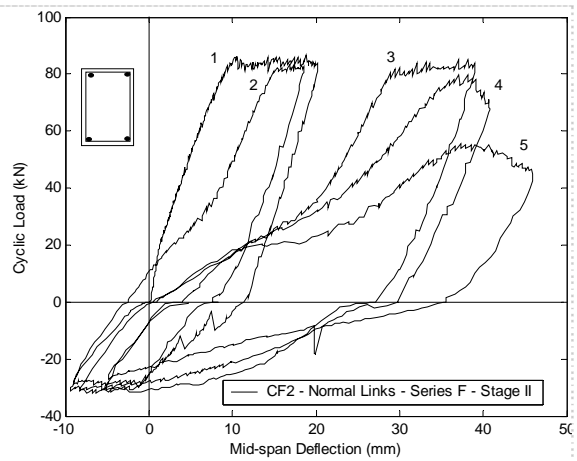


Fig. 7 Cyclic Load Deflection Curve for CF2 (Normal Links)

Table 3. Displacement Ductility Factors for Different Cycles

Cycle no:	1	2	3	4	5	6	7	8
$\cong \mu$ for CF1	+2	+2	+3	+3.5	+4	+4	+4	+4
$\cong \mu$ for CF2	+2	+2	+3	+3.5	+4	-	-	-

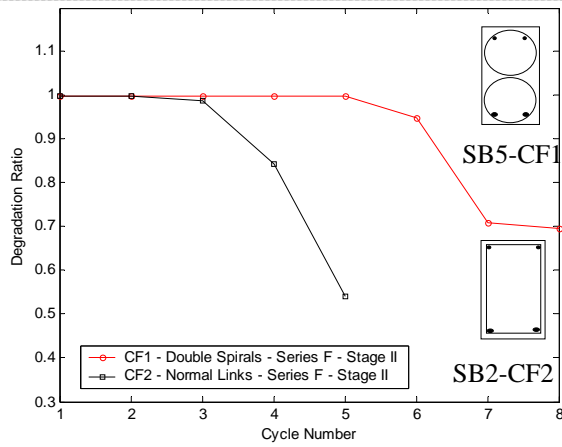


Fig. 8 Degradation of Strength for Beam CF1 and CF2 with Cyclic Loading.

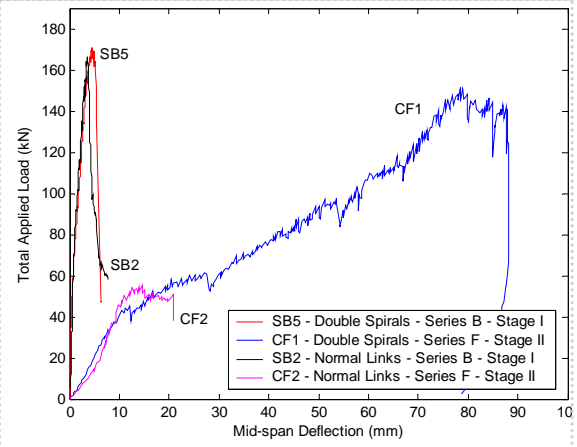


Fig. 9 Shear Test Comparison for Beam CF1 and CF2 After Cyclic loading with SB2 and SB5



Beam CF1 – Series F Stage II



Beam CF2 – Series F Stage II

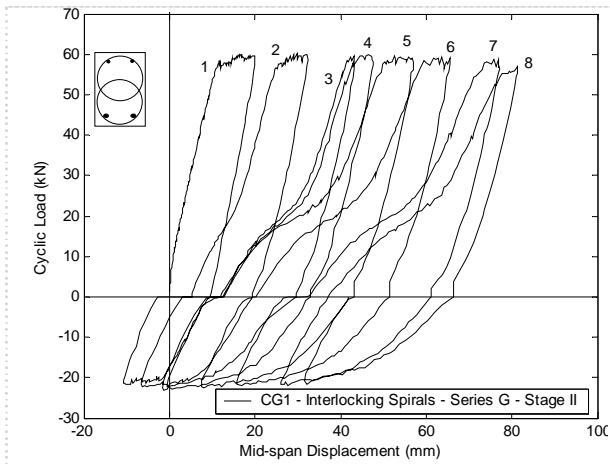


Fig. 10 Cyclic Load Deflection Curve for CG1 (Interlocking Spirals)

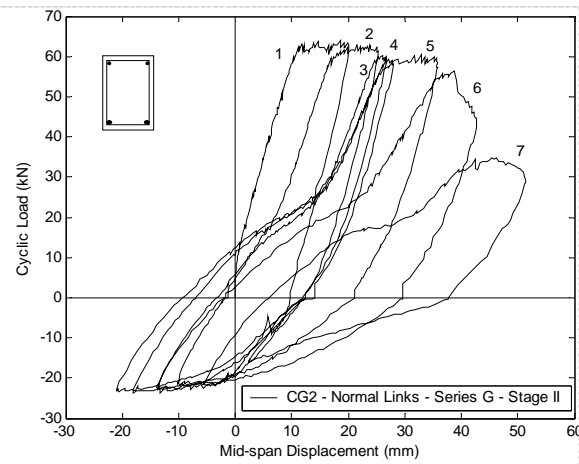


Fig. 11 Cyclic Load Deflection Curve for CG2 (Normal Links)

Table 4. Displacement Ductility Factors for Different Cycles

Cycle no:	1	2	3	4	5	6	7	8
$\cong \mu$ for CG1	+2	+3	+4	+4.5	+5.5	+6.5	+7.5	+8
$\cong \mu$ for CG2	+2	+2.5	+2.5	+2.5	+3.5	+4	+5	-

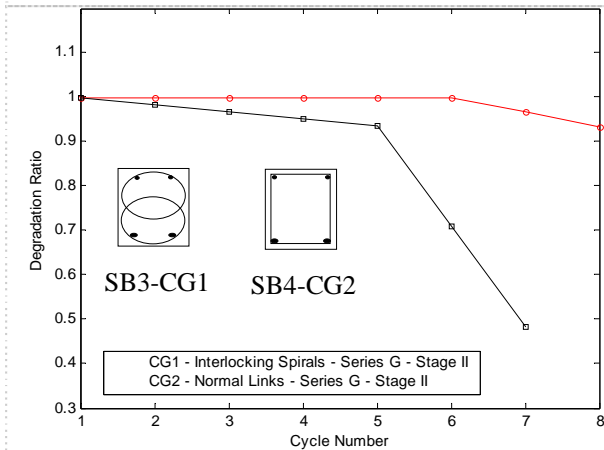


Fig. 12 Degradation of Strength for Beam CG1 and CG2 with Cyclic Loading.

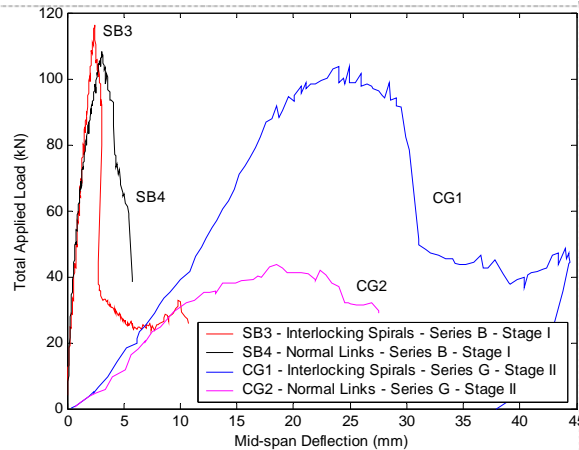


Fig. 13 Shear Test Comparison for Beam CG1 and CG2 After Cyclic Loading with SB3 and SB4



Beam CG1 – Series G Stage II



Beam CG2 – Series G Stage II

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