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CYCLIC BEHAVIOUR OF BEAM COLUMN JOINT RETROFITTED WITH SIMCON LAMINATES

C. Antony Jeyasehar and K. Ravichandran*
Department of Civil and Structural Engineering, Annamalai University, Annamalainagar-608002

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ABSTRACT

An investigation on the performance of reinforced concrete beam column joints under cyclic loading is reported. Joints have been cast with adequate and deficient shear capacity and bond of reinforcements at the beam column joint. Fiber Reinforced Cementitious Composites (HPFRCCs) like Slurry Infiltrated Mat CONcrete (SIMCON) have been applied on the joints in different volume fraction and aspect ratios. The column subjected to an axial force while the beams are subjected to cyclic load with controlled displacement. The displacement is increased monotonically using a hydraulic push and pull jack. The hysteretic curves of the specimen have been plotted. The energy dissipation capacity of retrofitted beam column joints with various SIMCON configurations has been compared. In addition, comparisons were made between experimental and analytical results of control specimen and SIMCON retrofitted specimen. The results show that the strengthened beam column joint exhibit increased strength, stiffness, energy dissipation and composite action until failure.

Keywords: Composite beam column joint; SIMCON; retrofitting; fiber reinforced concrete; cyclic loading; hysteretic curves

1. INTRODUCTION

Beam column joint is an important part of reinforced concrete (RC) moment resisting frames in the earthquake prone areas. The cross sections of beams and columns close to the joints in RC structures are critical, and under the effect of strong earthquake motion they are subjected to large bending moments and shear forces. Beam column joint in moment resisting frames are crucial zones that control the effective transmission of forces in the structure. In normal design practice for gravity loads, the design check for joints is not

* E-mail address of the corresponding author: krcrithiesh@gmail.com (K. Ravichandran)

usually critical in reinforced concrete frames and hence not warranted in general. However, failures of reinforced concrete frames during recent earthquakes have revealed heavy distress in the joints and resulted in the collapse of several structures due to joint shear failure. Designers should guarantee that the joint in a moment resisting frame is adequate in terms of overall member sizes in the initial design stage itself, and subsequently check the joint adequacy and provide appropriate reinforcement detailing.

2. LITERATURE REVIEW

Reinforced concrete structures built in zones of low to medium seismicity still do not take seismic effect into consideration. The reinforcement details of such structures though conform to the general construction code of practice may not adhere to the latest seismic provisions.

Structural engineers often consider current seismic code details for reinforced concrete framed structures impractical. A beam column joint becomes structurally less efficient when subject to large lateral loads, such as strong wind, earthquake, or explosion.

In these areas, high percentages of transverse hoops in the core of joints are needed in order to meet the requirement of strength, stiffness and ductility under cyclic loading. Provisions of high percentage of hoops cause congestion of steel leading to construction difficulties. The performance of beam column joint under seismic conditions has been a research topic for many years. Paulay [1] used the laws of statics and postulated that joint shear reinforcement is necessary to sustain the diagonal compression field rather than to provide confinement to compressed concrete in a joint core. Tsonos et al [2] suggested that the use of crossed inclined bars in the joint region is one of the most effective ways to improve the seismic resistance of exterior reinforced concrete beam column joints. Murty et al [3] have tested the exterior beam column joint subject to static cyclic loading by changing the anchorage detailing of main reinforcement and shear reinforcement. The authors reported that the practical joint detailing using hairpin-type reinforcement is a competitive alternative to closed ties in the joint region. Jing et al [4] conducted experiment on interior joints by changing the beam reinforcement detailing pattern at the joint core. Diagonal steel bars in the form of “obtuse Z” were installed in two opposite direction of the joint. The authors found that the non-conventional pattern of reinforcement provided was suitable for joints in regions of low to moderate seismicity. Lakshmi et al [5] have developed analytical modeling of beam column joint subjected to cyclic loading by using ANSYS. The anchorage length requirements for beam bars, the provision of transverse reinforcement and the role of stirrups in shear transfer at the joint are the main issues found from the literatures reviewed. A study of the usage of additional cross-inclined bars at the joint core [2] shows that the inclined bars introduce an additional new mechanism of shear transfer and diagonal cleavage fracture at joint will be avoided. However, there are only limited experimental and analytical studies for the usage of non-conventional detailing of exterior joints. In spite of the wide accumulation of test data, the influence of cross inclined bars on shear strength of joint has not been mentioned in major international codes. In this work, an attempt has been made to improve the confinement of core concrete without congestion of reinforcement in joints. The performance of exterior joint assemblages detailed for earthquake loads as per IS

13920:1993 [6] and detailed as per current Indian construction code of practice IS 456:2000 [7] are compared with the retrofitted specimens. The experimental results are validated with the analytical model developed using finite element software package ANSYS.

3. EXPERIMENTAL INVESTIGATION

3.1 Slurry infiltrated mat concrete (SIMCON)

A promising new way of resolving this problem is to selectively use advanced composites such as High Performance Fibre Reinforced Cementitious Composites (HPFRCCs). The HPFRCC used here is SIMCON. This can also be considered a pre - placed fibre concrete, similar to SIFCON. However, in the making of SIMCON, the fibres are placed in a "mat form" rather than as discrete fibres. The advantage of using steel fibre mats over a large volume of discrete fibres is that the mat configuration provides inherent strength and utilizes the fibres contained in it with very much higher aspect ratios.

3.2 Preliminary studies on SIMCON

Preliminary experimental study was conducted to determine the elastic properties of SIMCON with volume fraction of 5.5 and aspect ratio of 300 and 400. SIMCON laminates of size 125 × 25 × 500 mm were cast with volume fraction of 5.5 percent and aspect ratio of 300 and 400.The diameter of the individual fiber is 0.5 mm. The fiber mats were kept in the mould and were grouted; the cement slurry was mixed in a mortar mixer with super plasticizer for improving workability. Mixing ratio of the cement slurry is given below:

Sand / cement - 0.50
Water / cement ratio - 0.30
Superplastiziers / cement - 0.025

Strength parameters

Experiments were conducted to ascertain the strength parameters and the observed parameters are given below:

Mean compressive strength - 88 N/mm^2
Mean tensile strength - 70 N/mm^2
Modulus of elasticity - 2.7×10^4 N/mm^2
Density of SIMCON mat = 7695.97 kg/m^3
Density of SIMCON laminates = 1800 kg/m^3
Mean Compressive Strength of SIMCON laminates, f_{cm} = 88 N/mm^2
Mean Tensile Strength of SIMCON laminates, f_{ct} = 17 N/mm^2
Modulus of Elasticity of SIMCON laminates, E_r = 3.20×10^4 N/mm^2

3.3 Casting of RC beam column joint

The beam column joint consisted of both column and beam 230×230 mm size. Six specimens were cast out of which three are based on non ductile (Type A) and remaining three based on ductile detailing (Type B). In each case one specimen was considered as control specimen.

All the Type A specimens had identical dimensions and were reinforced such that they would represent non-ductile detailed exterior joint of RC frame as per IS456-2000 code recommendations. Reinforcement consists of four 12 mm diameter rebars in the column, two 12 mm diameter rebars in each side of the beam 8 mm stirrups at a spacing of 150 mm in the column and beam uniformly (Figure 1).

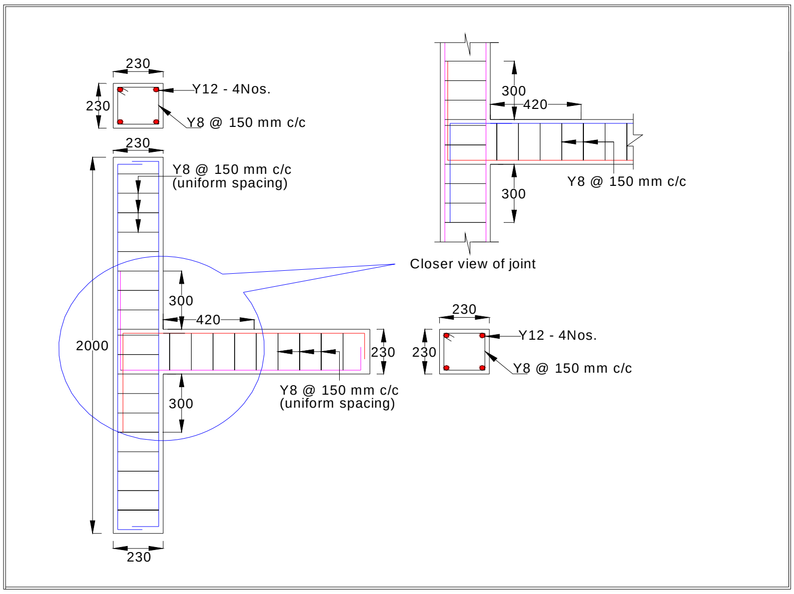


Figure 1. Reinforcement details for non ductile joint (Type A)

All the Type B specimens had identical dimensions and were reinforced such that they would represent ductile detailed exterior joint of RC frame as per IS13920-1993 code recommendations. Reinforcement consists of four 12 mm diameter rebars in the column, two 12 mm diameter rebars in each side of the beam and 8 mm stirrups at a spacing of 100 mm in the column and beam at the non anchorage zone and 8 mm stirrups at a spacing of 75 mm at the anchorage zone (Figure 2). A short description of the specimens is given in Table 1.

Table 1: Description of test specimens

Sl. No.	Specimen Designation	Type of Reinforcement	Retrofitting Methodologies
1	NDA-1	non ductile	Control specimen
2	DDB-1	Ductile	Control specimen
3	NDA-S1	non ductile	SIMCON (aspect ratio: 300)
4	NDA-S2	non ductile	SIMCON (aspect ratio: 400)
5	DDB-S1	Ductile	SIMCON (aspect ratio: 300)
6	DDB-S2	Ductile	SIMCON (aspect ratio: 400)

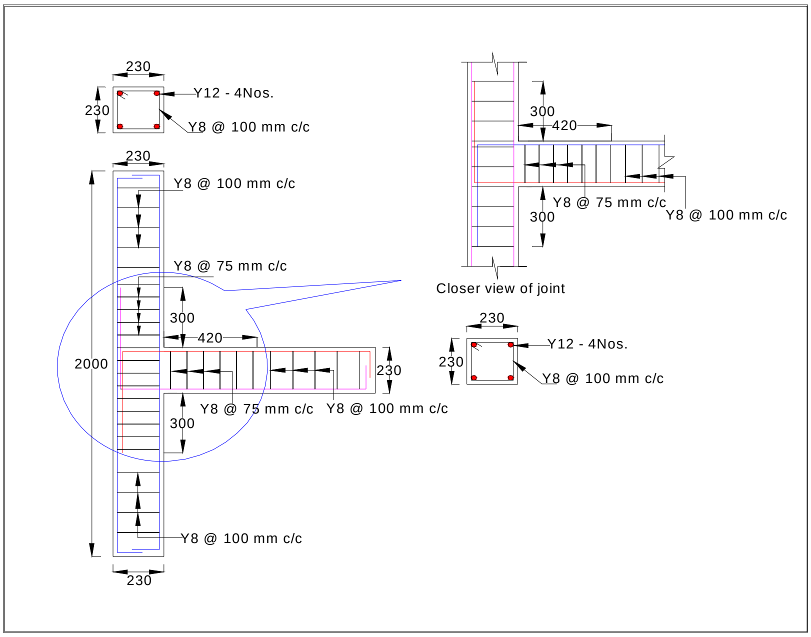


Figure 2. Reinforcement details for ductile joint (Type B)

3.4 Bonding of SIMCON laminates

SIMCON laminates were used for externally strengthening the RC beam column joint (Figure 3). After surface preparation, epoxy bonding systems were adopted to bond the laminates and bond line thickness of 2.0 mm was kept constant for all the test specimens.

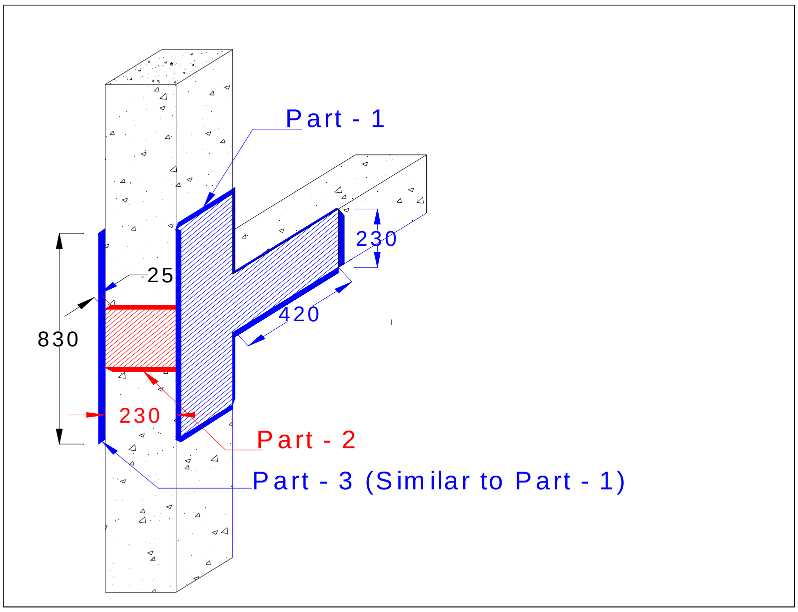


Figure 3. SIMCON wrapping system

3.5 Testing arrangement

The schematic view of the test set up is shown in Figure 4. The joint assemblages were subjected to axial load and reverse cyclic loading. A 500kN hydraulic jack mounted vertically to the loading frame was used for simulating the axial gravity load on the column. A constant axial load of 100kN, which is about 20 percent of the axial capacity of the column was applied to the columns for holding the specimen in position and to simulate column axial load. Two ends of the column were given an external axial hinge support, in addition to two lateral hinge support provided at the bottom and top of the column. Another 500 kN capacity hydraulic push and pull jack was used to apply reverse cyclic load to the beam portion of the beam column joint The point of application of the cyclic load was at 50 mm from the free end of the beam. The test was displacement controlled and the specimen was subjected to an increasing cyclic displacement up to the failure. The displacement increment was 5 mm, for push and pull for the test specimen. The specimens were instrumented with linear variable differential transducer having range ± 75 mm to measure the displacement at loading point.

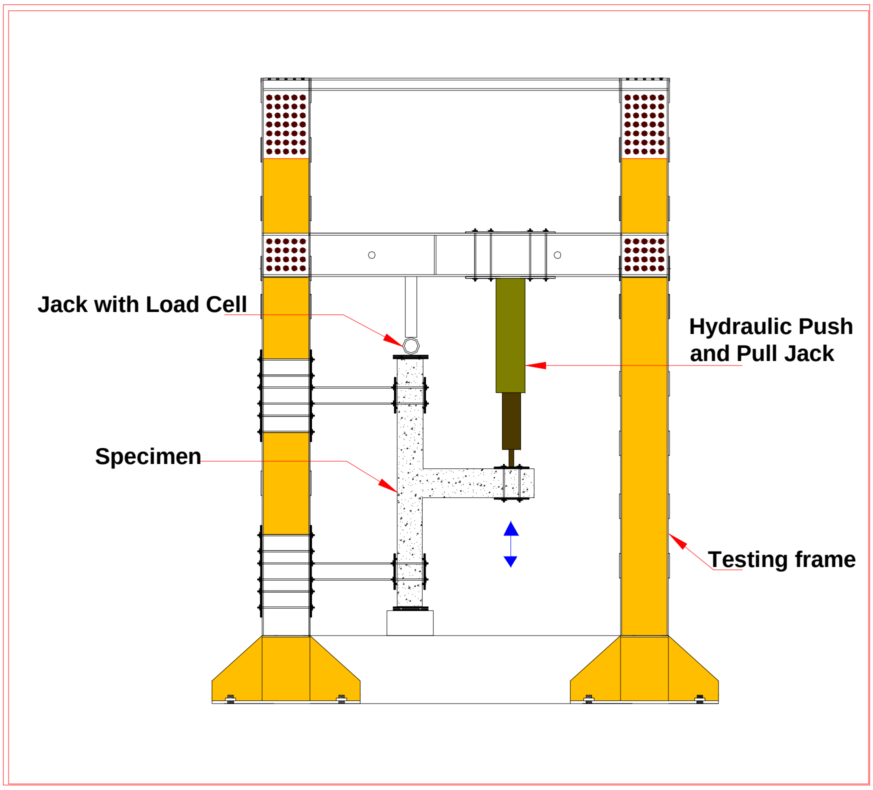


Figure 4. Schematic view of test set up

3.6 Beam column joint control specimen

Hysteresis behaviour of NDA-1 and DDB-1 specimen are shown in figure 5. For NDA-1, the maximum load observed is 25kN in push and 18 kN in pull respectively and the specimen failed in 30 mm displacement. Based on the hysteresis behavior energy dissipation and stiffness degradation per cycle are worked out. The total cumulative energy dissipation observed is 803.3kN mm (Table 2). The stiffness degraded from 2.9 kN / mm to 0.7 kN / mm. For DDB-1, the maximum load observed is 28.2 kN in push and 20.2 kN in pull respectively and the specimen failed in 35 mm displacement. The total cumulative energy dissipation observed is 1113.2 kN mm. The stiffness degraded from 3.4 kN / mm to 0.8 kN / mm. The increase in energy dissipation for ductile detailed specimen DDB-1 when compared to non ductile detailed specimen is 27.8 percent.

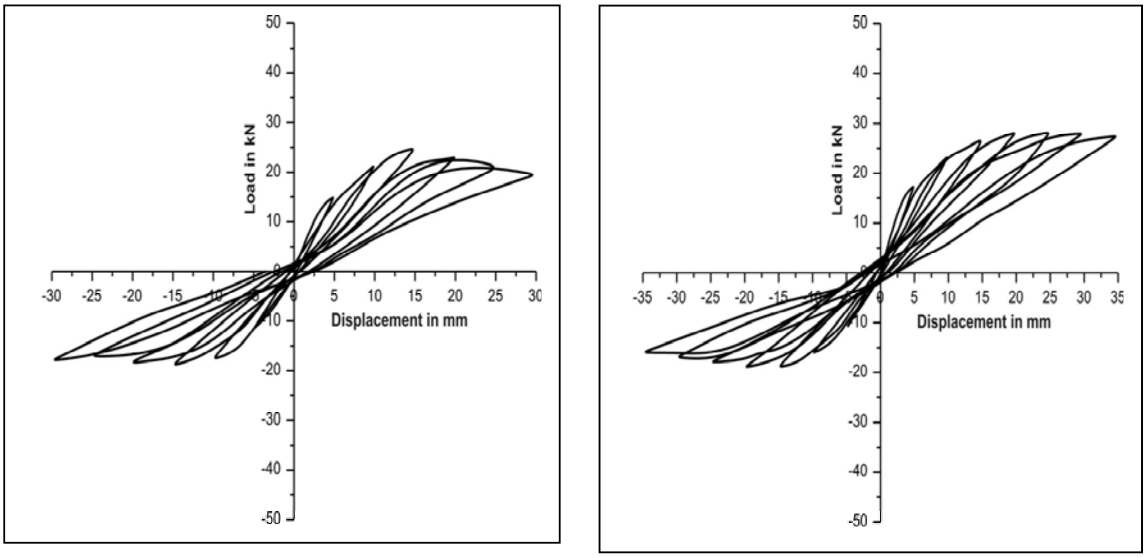


Figure 5. Hysteresis behavior of specimen NDA-1 and DDB-1

Table 2: Energy dissipation and stiffness at various displacements

Displacement mm	Energy dissipated (kN mm)		Stiffness (kN/mm)	
	NDA-1	DDB-1	NDA-1	DDB-1
5	20.6	21.4	2.9	3.4
10	80.4	83.3	2.2	2.3
15	179.9	206.2	1.7	1.8
20	334.1	356.9	1.2	1.4
25	550.3	582.2	0.9	1.1
30	803.3	839.3	0.7	0.9
35	-	1113.2	-	0.8

The cumulative energy dissipation and stiffness for NDA-1 and DDB-1 specimen are given in Figure 6. The increase in energy dissipation of ductile detailed beam is 27.83 percent when compared with the non ductile detailed beam. The energy dissipation at first cycle of displacement for NDA-1 specimen is 20.6 kN mm and DDB-1 specimen is 21.4 kN mm. The stiffness at various cycle of loading, it can be seen that the stiffness degrades continuously in all the cycles. The stiffness at first cycle of displacement for NDA-1 specimen is 2.9 kN/mm and the DDB-1 specimen is 3.4 kN/mm.

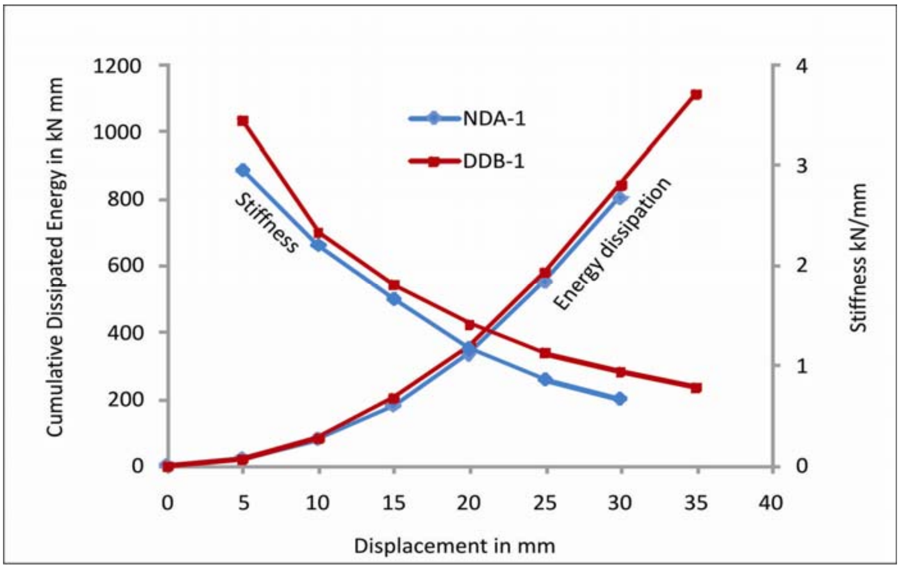
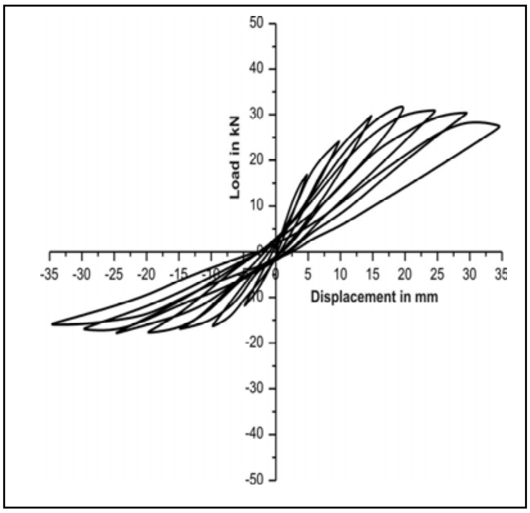


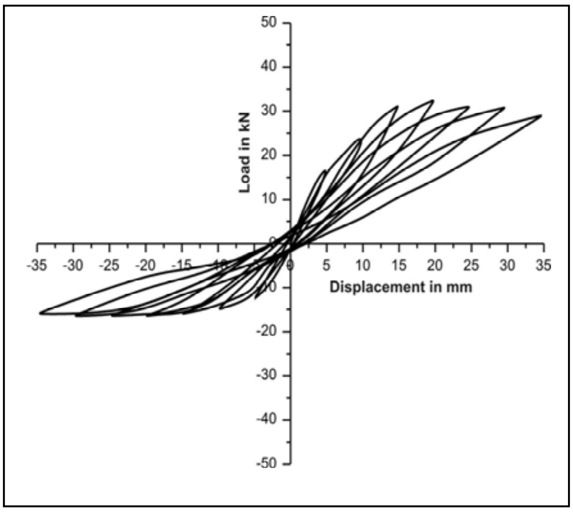
Figure 6. Cumulative energy dissipation and stiffness vs. displacement

3.7 Beam column joint specimen retrofitted with SIMCON

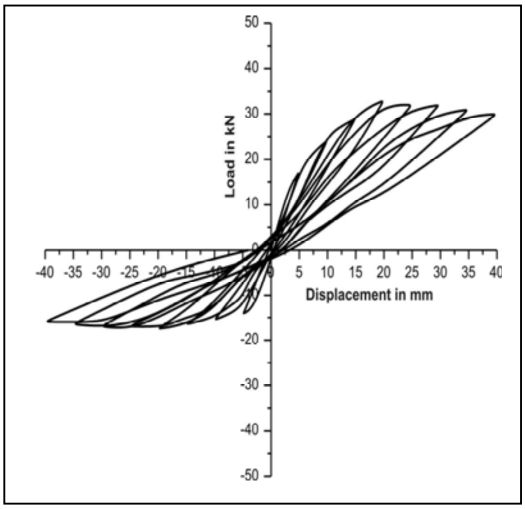
Hysteresis behaviour of SIMCON retrofitted specimen are shown in Figure 7. For NDA-S1 the maximum load observed is 32.5kN in push and 21kN in pull respectively and the specimen failed in 35 mm displacement. Based on the hysteresis behavior energy dissipation and stiffness degradation per cycle are evaluated and are given in Tables 3 and 4. The variation of cumulative energy dissipation and stiffness with displacement is shown in Figures 8 and 9. The total cumulative energy dissipation observed is 1121.1Kn/mm. The stiffness degraded from 3.4 kN/mm to 0.8 kN/mm. For DDB-S1, the maximum load observed is 33kN in push and 22kN in pull respectively and the specimen failed in 40 mm displacement. The total cumulative energy dissipation observed is 1627.9kN/mm. The stiffness degraded from 3.4 kN/mm to 0.8 kN/mm. For NDA-S2, the maximum load observed is 32.7kN in push and 21.5kN in pull respectively and the specimen failed in 35 mm displacement. The total cumulative energy dissipation observed is 1189.1kN/mm. The stiffness degraded from 3.5 kN/mm to 0.8 kN/mm. For DDB-S2 the maximum load observed is 33.5 kN in push and 22.9kN in pull respectively and the specimen failed in 40 mm displacement. The total cumulative energy dissipation observed is 1635.5 kN mm. The stiffness degraded from 3.5 kN/mm to 0.8 kN/mm. The increase in total cumulative energy dissipation for NDA-S1 when compared to NDA-1 is 28.3 percent and that for NDA-S2 is 32.4 percent. This shows SIMCON with aspect ratio 400 performs better than with aspect ratio 300. Further, the percentage increase in total cumulative energy dissipation for SIMCON retrofitted specimen is more than the percentage increase of energy dissipation in the case of ductile detailed specimen DDB-1 compared to non ductile detailed specimen NDA-1.This clearly indicates that SIMCON retrofitting can be used as a substitute for ductile detailing if it is absent in the existing structures. The increase in total cumulative energy dissipation for DDB-S1when compared to DDB-1 is 31.6 percent and that for DDB-S2 is 31.9 percent. This shows that the aspect ratio of SIMCON does not have any effect on retrofitting of ductile detailed specimen. Further, the increase in total cumulative energy dissipation clearly indicates that the SIMCON retrofitting is an effective methodology for retrofitting of existing ductile detailed structures if the seismic zone is upgraded.



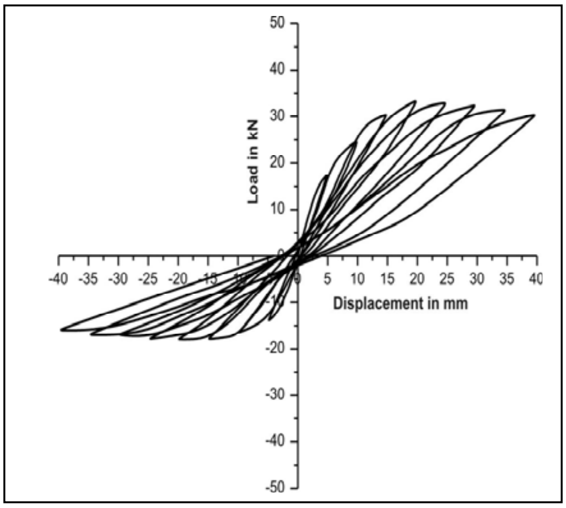
(a) NDA-S1



(b) NDA-S2



(c) DDB-S1



(d) DDB-S2

Figure 7. Hysteresis behavior of SIMCON retrofitted specimen

Table 3: Energy dissipation at various displacements

Displacement mm	Energy dissipated (kN mm)				
	NDA-1	NDA-S1	DDB-S1	NDA-S2	DDB-S2
5	20.6	21.3	28.2	25.6	29.7
10	80.4	88.3	91.3	99.5	101.9
15	179.9	194.9	201.3	231.8	218.2
20	334.1	362.0	370.8	409.8	389.9
25	550.3	584.1	621.7	642.3	628.3
30	803.3	829.6	906.2	907.1	921.8
35	-	1121.1	1222.6	1189.1	1232.3
40	-	-	1627.9	-	1635.5

Table 4: Stiffness at various displacements

Displacement mm	Stiffness (kN/ mm)				
	NDA-1	NDA-S1	DDB-S1	NDA-S2	DDB-S2
5	2.9	3.4	3.4	3.5	3.5
10	2.2	2.5	2.4	2.5	2.5
15	1.7	2.0	1.9	2.1	2.0
20	1.2	1.6	1.7	1.6	1.7
25	0.7	1.2	1.3	1.2	1.3
30	0.7	1.0	1.1	1.1	1.1
35	-	0.8	0.9	0.8	0.9
40	-	-	0.8	-	0.8

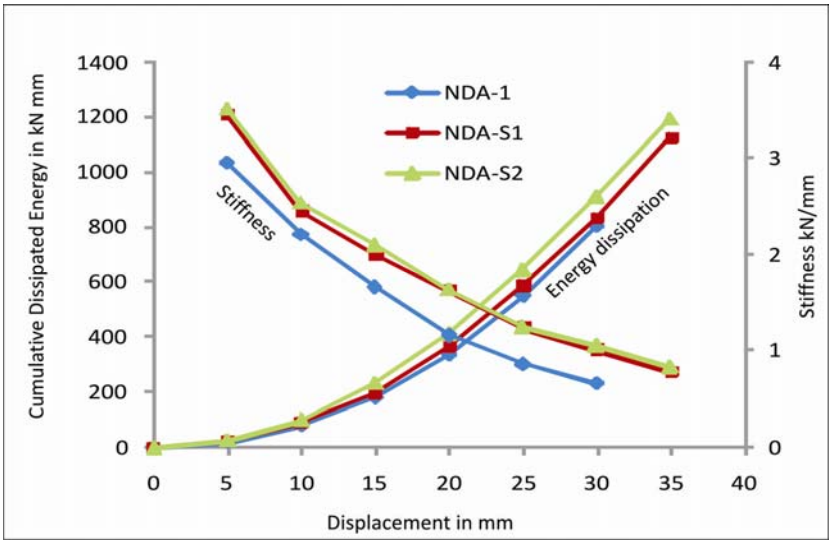


Figure 8. Cumulative energy dissipation and stiffness vs. displacement

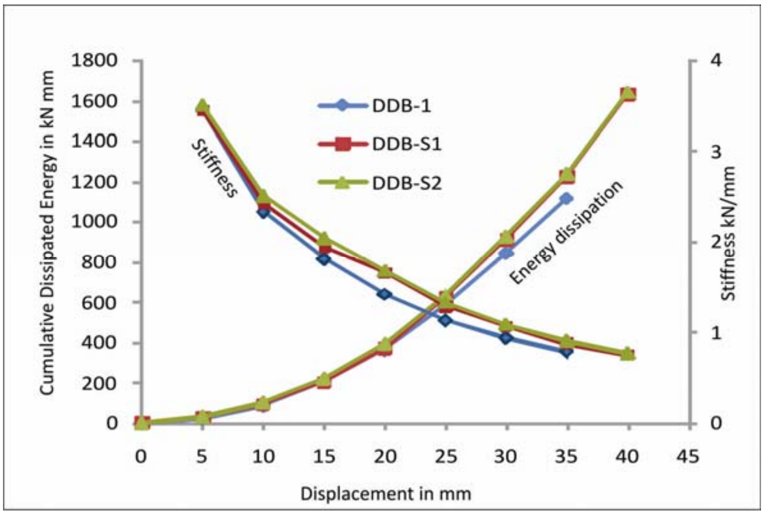
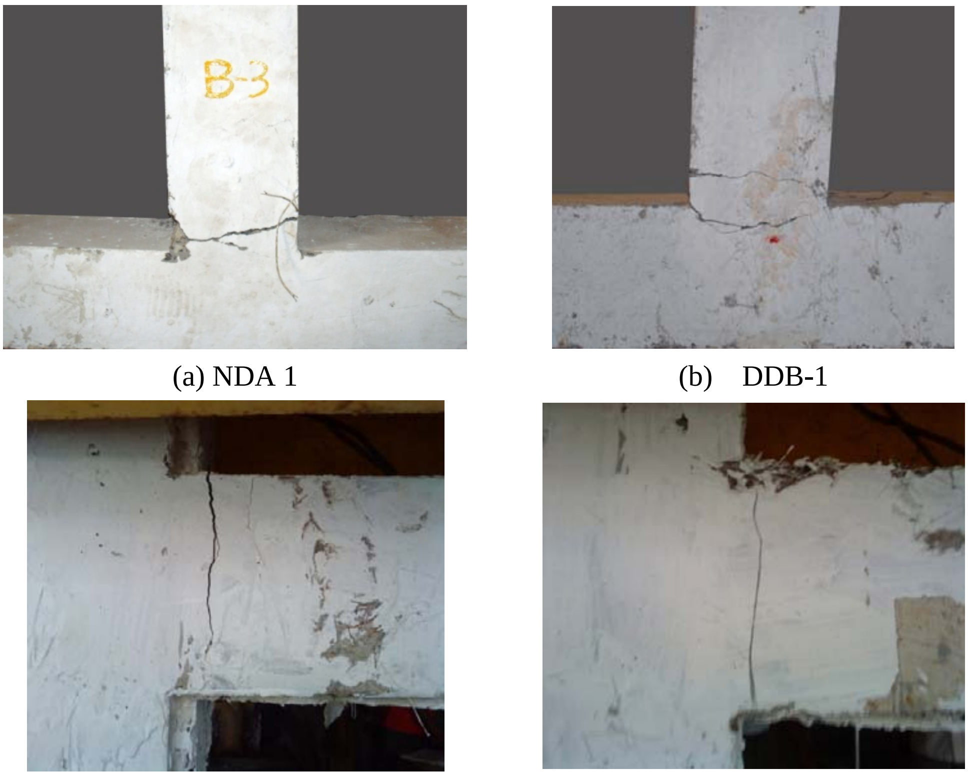


Figure 9. Cumulative energy dissipation and stiffness vs. displacement

3.8 Crack pattern of control specimen

The crack patterns of the entire tested specimen are shown in figure 10. The entire specimen failed in the beam portion, yielding of steel has been observed at the point of failure. Strain gauges are bonded in the beam portion, but these strain gauges are deboned at the reach of two cycles and the allowable deflection.



(a) NDA 1 (b) DDB-1

(c) NDA-S1 (d) NDA-S2

(e) DDB-S1 (f) DDB-S2

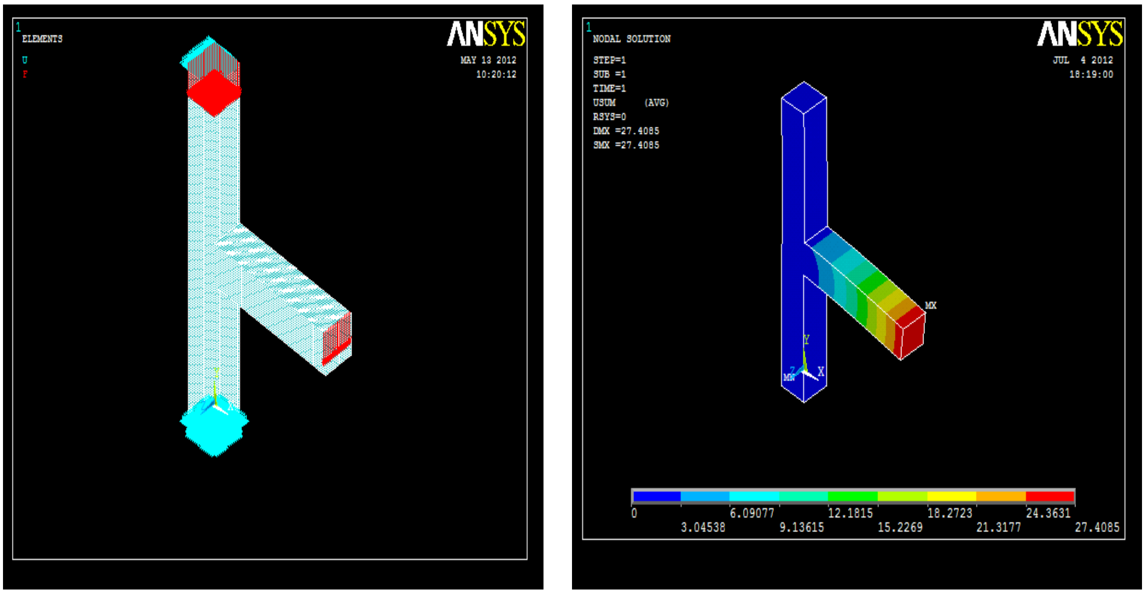
Figure 10. Crack pattern of tested beam column joints

4. NUMERICAL ANALYSIS (ANSYS)

A full 3D finite element analysis has been carried out using ANSYS general purpose finite element software. The analysis presented in this paper assumes that the beam column joint is subjected to cyclic loading. Further experimental results are presented for beam column joint for comparison. The concrete has been modeled using eight noded solid element (SOLID 65) specially designed for concrete, capable of handling plasticity, creep, cracking in tension and crushing in compression. The characteristics of the adopted element being non linear, requires an iterative solution. In this analysis, the compressive strength of concrete (f_{ck}) is taken as 30.30 MPa and tensile strength of concrete (f_t) is considered as 3.5 MPa. The elastic modulus (E_s) is 25735 MPa. The reinforcing steel has been modeled using a series of two noded link element (LINK 8). The material properties associated with link elements include an initial yield stress 448 MPa. The SIMCON laminates has been modeled using eight noded multi layered sold element (SOLID 46).The material properties of SIMCON laminates, are listed in section3.3. The adhesive layer has been modeled using 3D isotropic elements (SOLID 45). The material property modulus of elasticity is (E_s) 1500 MPa.

4.1 Modeling of beam-column joint

The boundary conditions were exactly simulated as in the test set up shown in Figure 11(a). Horizontal and vertical restraints, representing a pin connection were applied at the top and bottom of the column. At the end of beams, only vertical displacement were provided to simulate the cyclic load conditions used in the test. A constant axial load of 100 kN was applied to top end of the column. The vertical displacement at the beam end was applied in a slowly increasing monotonic manner, with results recorded for every 5 mm vertical displacement up to failure. The deflected shape of the model is shown in Figure 11(b).

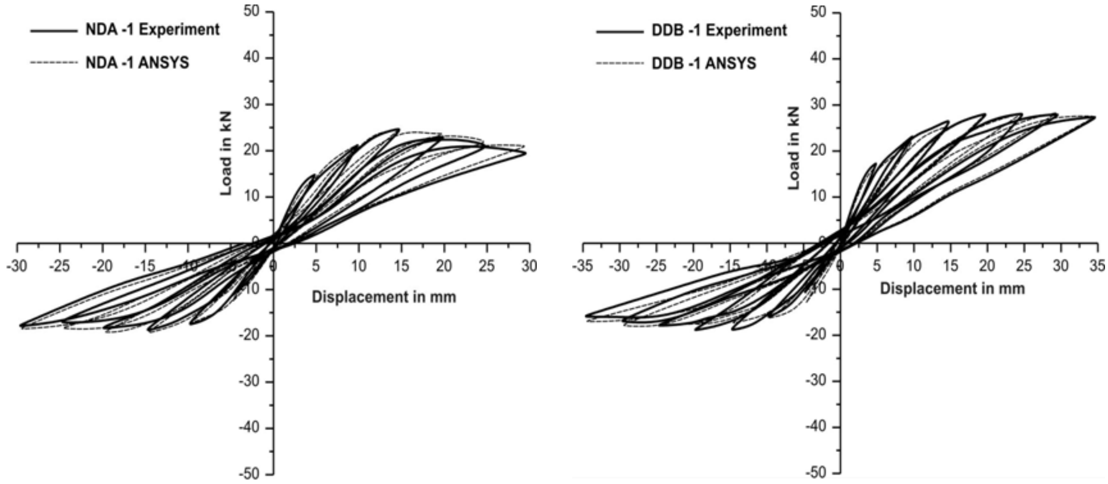


(a) ANSYS model (b) Deflected shape

Figure 11. ANSYS model and deflected shape of Beam column joint

4.2 Beam column joint- control specimen

Hysteresis behavior of NDA-1 specimen obtained using ANSYS is shown in figure 12 along with the one obtained from experiment. The maximum load observed is 24kN in push and 18.5kN in pull respectively using ANSYS and 25kN in push and 18.5kN in pull respectively in the case of experiment and in both cases the specimen failed at 30mm displacement. Based on the hysteresis behavior, energy dissipation and stiffness degradation per cycle are evaluated and are given in Table 5. The variation of cumulative energy dissipation and stiffness with displacement is shown in Figure 13. The analytical value of total cumulative energy dissipation is 669.1kN/mm when compared to the experimental value of 803.3 kN mm. The stiffness degraded from 2.8 kN/mm to 0.6 kN/mm in the case of ANSYS and from 2.9 kN/mm to 0.7 kN/mm in the case of experiment. For DDB-1 specimen the maximum load observed is 27.5 kN in push and 19.5 kN in pull respectively using ANSYS and 28.2 kN in push and 20.2 kN in pull respectively in the case of experiment and in both cases the specimen failed at 35mm displacement. The variation of cumulative energy dissipation and stiffness with displacement for DDB-1 is shown in figure 14. The analytical value of total cumulative energy dissipation for DDB-1 is 954.5 kN mm when compared to the experimental value of 1113.2 kN mm. The stiffness for DDB-1 degraded from 3.4 kN/mm to 0.8 kN/mm in the case of experiment and analytical value from 3.3 kN/mm to 0.8 kN/mm. This indicates that the analytical behavior closely predicts the experimental behavior.



(a) NDA-1 (b) DDB-1

Figure 12. Hysteresis behavior of specimen NDA-1 and DDB-1 (Experiment vs. ANSYS)

Table 5: Energy dissipation at various displacements

Displacement mm	Energy dissipated (kN mm)				Stiffness (kN / mm)			
	NDA-1		DDB-1		NDA-1		DDB-1	
	Experiment	ANSYS	Experiment	ANSYS	Experiment	ANSYS	Experiment	ANSYS
5	20.6	17.3	21.4	18.0	2.9	2.8	3.4	3.3
10	80.4	69.5	83.2	71.8	2.2	2.1	2.3	2.2
15	179.9	163.8	206.2	175.4	1.7	1.6	1.8	1.7
20	334.1	287.4	356.9	304.2	1.2	1.2	1.4	1.4
25	550.3	451.9	582.2	489.5	0.9	0.8	1.1	1.1
30	803.3	669.1	839.3	696.4	0.7	0.6	0.9	0.9
35	-	-	1113.2	954.4	-	-	0.8	0.8

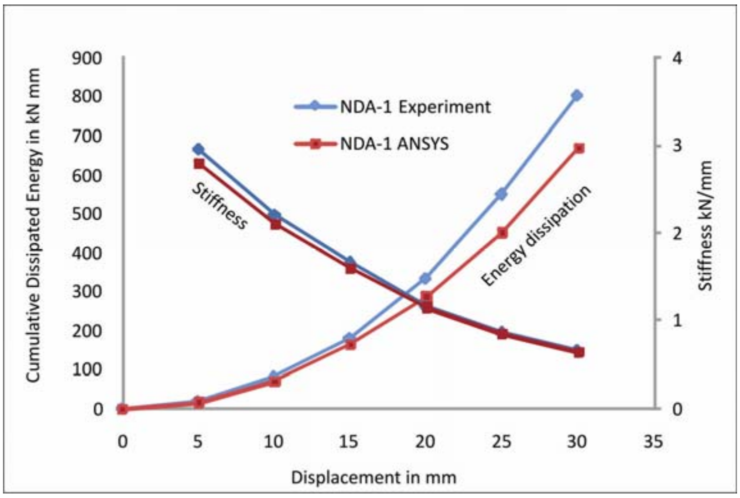


Figure 13. Cumulative energy dissipation and stiffness vs. displacement

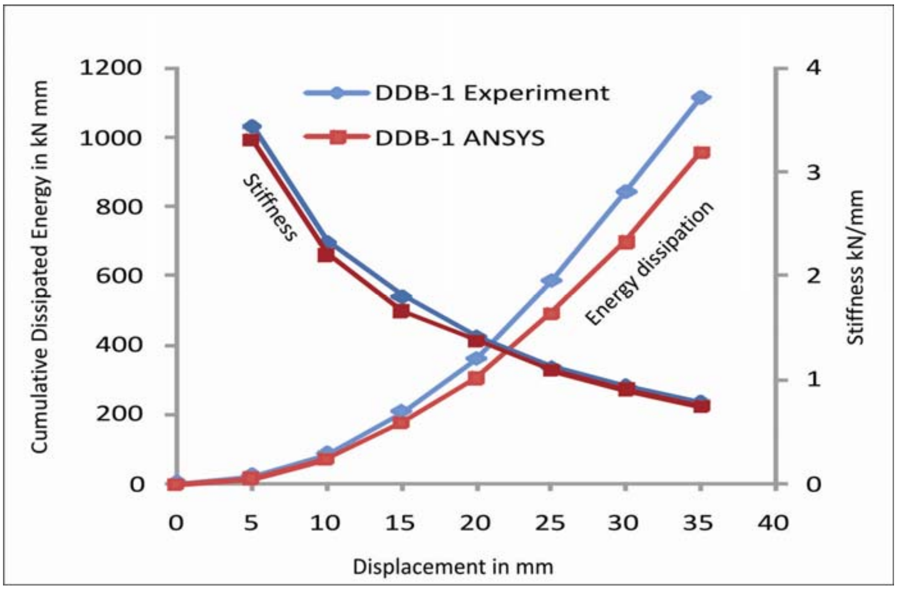
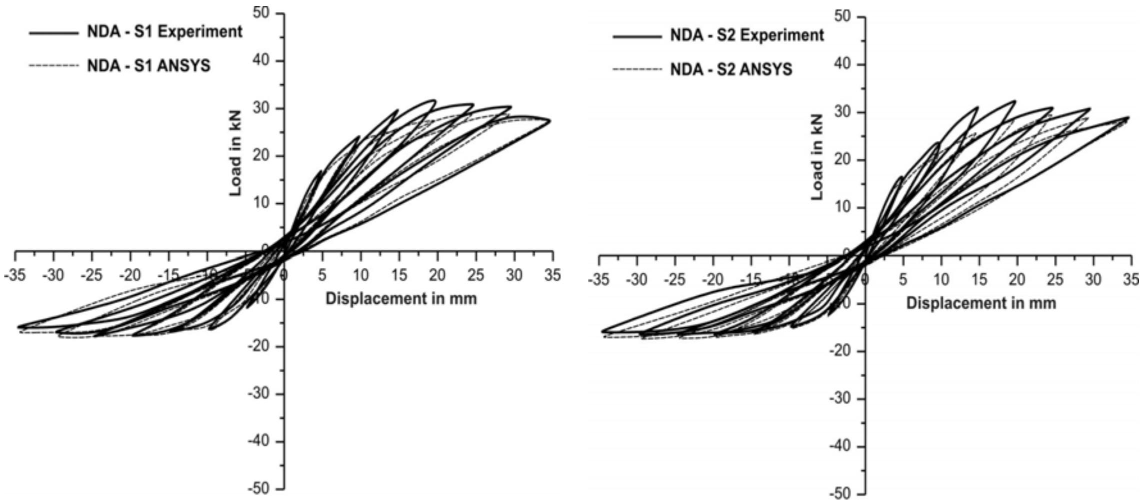


Figure 14. Cumulative energy dissipation and stiffness vs. displacement



(a) NDA-S1 (b) NDA-S2

Figure 15. Hysteresis behavior of specimen NDA-S1 and NDA-S2 (Experiment vs. Analytical)

4.3 Beam column joint- SIMCON retrofitted specimen (non ductile)

Hysteresis behaviour of NDA-S1 obtained using ANSYS is shown in Figure 15 along with the one obtained from experiment. The maximum load observed is 28.2kN in push and 19.5kN in pull respectively using ANSYS and 32.5kN in push and 21kN in pull respectively in the case of experiment and in both cases the specimen failed at 35mm displacement. Based on the hysteresis behavior energy dissipation and stiffness degradation per cycle are evaluated and are given in Tables 6 and 7. The variation of cumulative energy dissipation and stiffness with displacement is shown in Figure 16. The analytical value of total cumulative energy dissipation is 1059.8 kN/mm. The stiffness degraded from 3.1 kN/mm to 0.8 kN/mm. The experimental value of total cumulative energy dissipation for NDA-S1 is 1121.1 kN/mm. The stiffness of NDA-S1 degraded from 3.4kN/mm to 0.8 kN/mm. For NDA-S2 the maximum load observed is 29kN in push and 19.5kN in pull respectively using ANSYS and 32.7kN in push and 21.5kN in pull respectively in the case of experiment and in both cases the specimen failed at 35mm displacement. The variation of cumulative energy dissipation and stiffness with displacement is shown in Figure 16. The analytical value of total cumulative energy dissipation is 1120.4kN/mm. The stiffness degraded from 3.1 kN/mm to 0.8 kN/mm. The experimental value of total cumulative energy dissipation for NDA-S2 is 1189.1kN/mm. The stiffness in NDA-S2 degraded from 3.5kN/mm to 0.8 kN/mm

Table 6: Energy dissipation at various displacements

Displacement mm	**Energy dissipated (kN mm)**					
	NDA-1		**NDA- S1**		**NDA -S2**	
	Experiment	**ANSYS**	**Experiment**	**ANSYS**	**Experiment**	**ANSYS**
5	20.6	17.3	21.3	18.1	25.6	18.0
10	80.4	69.5	88.3	74.4	99.5	81.1
15	179.9	163.8	194.9	177.8	231.8	179.4
20	334.1	287.4	362.0	322.2	409.8	336.2
25	550.3	451.9	584.1	544.8	642.3	553.6
30	803.3	669.1	829.6	809.4	907.1	823.2
35	-	-	1121.1	1059.8	1189.1	1120.4

Table 7: Stiffness at various displacements

Displacemen t mm	**Stiffness (kN/mm)**					
	NDA-1		**NDA-S1**		**NDA- S2**	
	Experimen t	**ANSY S**	**Experimen t**	**ANSYS**	**Experiment**	**ANSYS**
5	2.9	2.8	3.4	3.1	3.5	3.1
10	2.2	2.1	2.5	2.2	2.5	2.2
15	1.7	1.6	2.0	1.7	2.1	1.7
20	1.2	1.2	1.6	1.4	1.6	1.4
25	0.9	0.9	1.2	1.1	1.2	1.1
30	0.7	0.6	1.0	0.9	1.1	0.9
35	-	-	0.8	0.8	0.8	0.8

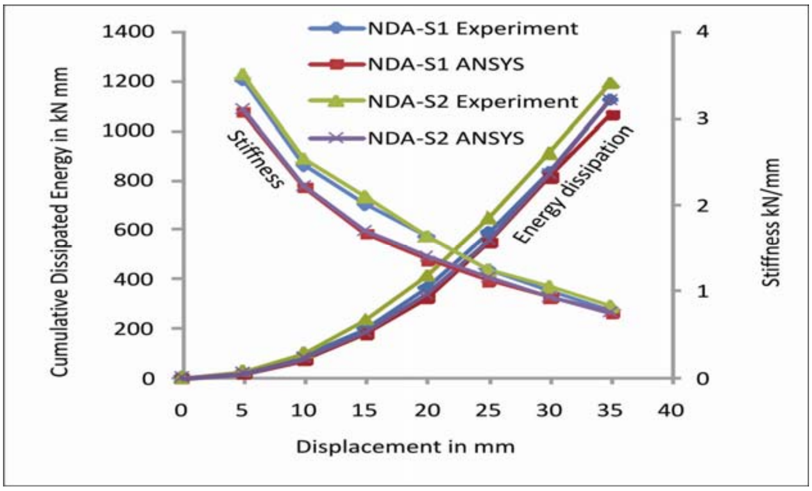
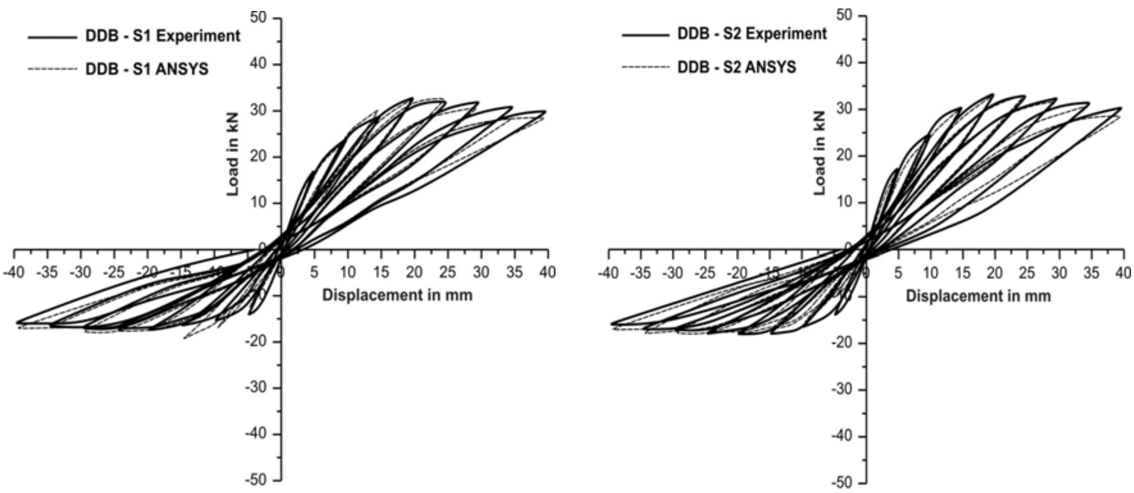


Figure 16. Cumulative energy dissipation and stiffness vs. displacement



(a) DDB-S1 (b) DDB-S2

Figure 17. Hysteresis behavior of specimen DDB-S1 and DDB-S2(experiment vs. analytical)

4.4 Beam column joint - SIMCON retrofitted specimen (ductile)

Hysteresis behaviour of DDB-S1 obtained using ANSYS is shown in Figure 17 along with one obtained from experiment. The maximum load observed is 32kN in push and 19.8kN in pull respectively using ANSYS and 33kN in push and 22.2kN in pull respectively in the case of experiment and in both cases the specimen failed at 40mm displacement. Based on the hysteresis behavior energy dissipation and stiffness degradation per cycle are evaluated and are given in Tables 8 and 9. The variation of cumulative energy dissipation and stiffness with displacement is shown in Figure 18. The analytical value of total cumulative energy dissipation is 1472.3kN mm and the stiffness degradation from 3.3kN/mm to 0.7kN/mm. The experimental value of total cumulative energy dissipation for DDB-S1 is 1627.9kN mm and the experimental stiffness of DDB-S1 degraded from 3.4kN/mm to 0.8 kN/mm. For DDB-S2, the maximum load observed is 32.5kN in push and 20.5kN in pull respectively using ANSYS and 33.5kN in push and 22.9kN in pull respectively in the case of experiment and in both cases the specimen failed at 40mm displacement. The analytical value of total cumulative energy dissipation is 1508.7kN mm and the stiffness degradation from 3.3 kN/mm to 0.8kN/mm. The experimental value of total cumulative energy dissipation DDB-S2 is 1635.47kN/mm. The experimental stiffness for DDB-S2 degraded from 3.5kN/mm to 0.8 kN/mm.

Table 8: Energy dissipation at various displacements

Displacement mm	**Energy dissipated (kN mm)**					
	DDB-1		**DDB- S1**		**DDB -S2**	
	Experiment	**ANSYS**	**Experiment**	**ANSYS**	**Experiment**	**ANSYS**
5	21.4	18.1	28.2	16.5	29.7	19.7
10	83.3	71.8	91.3	59.6	101.9	58.8
15	206.2	175.5	201.3	154.5	218.2	162.7
20	356.9	304.2	370.8	290.9	389.9	320.2
25	582.2	489.6	621.7	547.7	628.3	566.7
30	839.3	696.5	906.2	827.3	921.8	840.9
35	1113.2	954.5	1222.6	1121.5	1232.3	1138.3
40	-	-	1627.9	1472.3	1635.5	1508.7

Table 9: Stiffness at various displacements

Displacement mm	**Stiffness (kN/ mm)**					
	DDB-1		**DDB-S1**		**DDB-S2**	
	Experiment	**ANSYS**	**Experiment**	**ANSYS**	**Experiment**	**ANSYS**
5	3.4	3.3	3.4	3.3	3.5	3.3
10	2.3	2.2	2.4	2.3	2.5	2.4
15	1.8	1.7	1.9	2.0	2.0	2.1
20	1.4	1.4	1.7	1.6	1.7	1.6
25	1.1	1.1	1.3	1.2	1.3	1.3
30	0.9	0.9	1.1	1.0	1.1	1.0
35	0.8	0.8	0.9	0.8	0.9	0.8
40	-	-	0.8	0.7	0.8	0.7

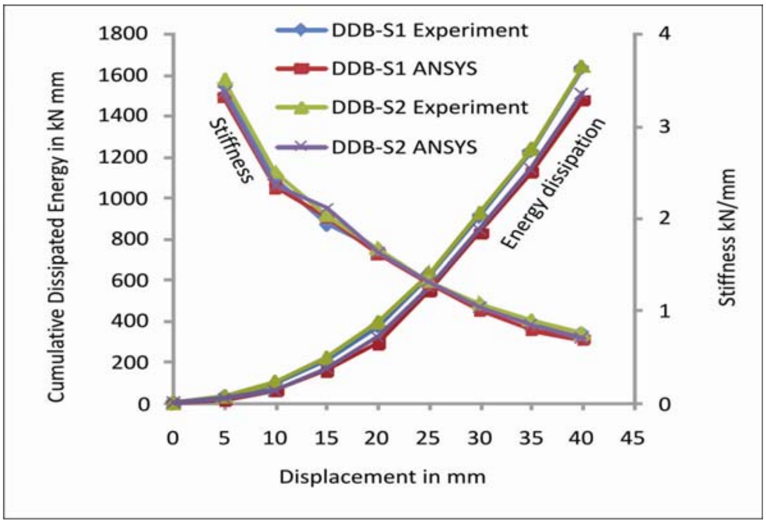


Figure 18. Cumulative energy dissipation and stiffness vs. displacement

5. CONCLUSIONS

Based on the experimental work and the numerical analysis, the following conclusions are drawn:

(i) The composite materials SIMCON can be efficiently used for seismic retrofitting of reinforced beam column joint.

(ii) The deficiency in cumulative energy dissipation in the case of non ductile reinforced beam column joint can be made good by SIMCON strengthening.

(iii) The increase in cumulative energy dissipation is 28.3 percent for non ductile and 31.6 percent for ductile reinforced concrete beam column joint strengthened by SIMCON.

(iv) ANSYS modeling closely predicts the experimental behavior of beam column joint.

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