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NEW DETAILS FOR REINFORCED CONCRETE BEAM-COLUMN JOINTS TO IMPROVE THEIR BEHAVIOR NEAR FAILURE

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Abstract

Even when results of tests of beam-column joints of reinforced concrete buildings subjected to earthquake-type load are widely available in literature, information about their behavior for large cycles of rapidly variable displacements, representative of the situation near collapse of the building, is difficult to find. Is also difficult to find information about seismic performance of arrangements of transverse reinforcement different from conventional 90° hoops.

In this work, about fifty close to real size (1/3 scale) RC corbel beams representing external beam-column joints of seismic frames or, better said, the part of the beam close to the joint, were tested subjected to an alternating rapidly variable cyclic load acting on the free end, simulating seismic solicitation. Large displacements were applied, most time destroying test specimen. Tests were performed at the Civil Engineering Department laboratory of the UTFSM.

Different ways of detailing beam, and joint were studied. Recent new tests, performed on elements with 45 deg. (and 135 deg.) inclined beam stirrups, confirm the ability of this type of shear reinforcement for keeping the integrity of building elements, retarding crushing and spalling of concrete, resulting in a gradual and ductile failure.

Improved 45 deg – 135 deg, easy to build shear reinforcement designs are proposed and some conceptual errors in placing bars of this type of reinforcement, and its consequences, are showed.

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Keywords: reinforced concrete; beam-column sub assemblages, seismic tests; diagonal compression failure 5

1. Introduction

The aim of this research is to find some ways to avoid damage concentration in reinforced concrete structures during earthquakes. This concern comes from observation of many collapsed 1/10 scale models tested on the seismic table at the UTFSM laboratory. During first stages of tests, under moderate solicitation, models carefully detailed following code regulations, develop ideal well distributed fine crack patterns. However when intense seismic solicitation is applied, cracks grow and open very fast in a few points, usually the end of beams, while close in the rest of the structure. Crushing and spalling caused for diagonal compression of concrete occur in those points, and the material escapes through spaces between reinforcing bars, reducing the capacity of plastic hinges to almost zero, and leaving the structure in danger. Actually, the same can be observed in real structures after a strong earthquake, as Fig. 1 shows. It seems to be that damage in modern reinforced concrete structures during recent earthquakes exceeded expectative.

Materials for constructing micro-concrete models that reproduce quite well the behavior of real reinforced concrete structures have been developed at UTFSM laboratories. The institution has a long experience in this technique, which began to be studied here after 1985 central Chile earthquake [1]. A previous paper [2] by the author, studies the behavior of beam-column joints models, closer to real size, looking for an explanation of the damage concentration observed on 1/10 scale models and in real structures. Recent new tests, performed on elements with 45 deg. (and 135 deg.) inclined beam stirrups, confirm the ability of this type of shear reinforcement for keeping the integrity of building elements, retarding crushing and spalling of concrete, resulting in a gradual and ductile failure.

Fig. 1 - Damage concentration in real structures and scale models

2. Previous research

Even when results of tests of beam-column joints of reinforced concrete buildings subjected to earthquake-type load are widely available in literature, information about their behavior for large cycles of rapidly variable displacements, representative of the situation near collapse of the building, has been difficult to find. Also, very little information was found about inclined transverse reinforcement in beams. It seems to be that inclined reinforcement in beams has been used only as main reinforcement of coupling beams between walls.

Interesting data was found in a recent paper by Azimi et al [3] who present tests of two different designs for a continuous transverse spiral reinforcement: single and twisted, to be used in beams and columns. They show that the last design, twisted, increase ductility almost three times respecting traditional 90° hoop reinforcement. Tegos and Penelis [4] presents also interesting results of tests of coupling beams where the main reinforcement is inclined forming a rhombic truss.

Some other possible solutions to the problem, such as steel fiber reinforcement, or carbon fiber membranes, have been considered. In this work performance of transverse reinforcement configured with common hoops inclined 45° - 135° is studied only.

3. Experimental program

3.1 Test specimens

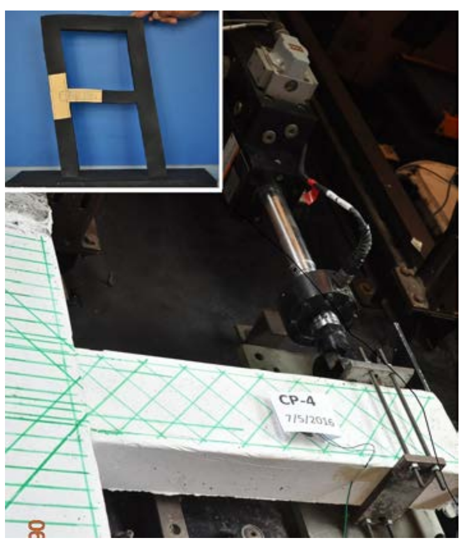

Fig. 2 Test specimen and MTS servo-hydraulic actuator used to apply the cycling load

About fifty close to real size (1/3 scale) reinforced concrete corbel beams anchored to a column segment representing external beam-column joints of seismic frames or, better said, the part of the beam close to the joint, were tested subjected to an alternating rapidly variable cyclic load acting on the free end, simulating seismic solicitation, as shown on Fig. 2. Large displacements were applied, most time destroying test specimens.

A list of relevant tests for this work are presented in Table 1. Dimensions of all beams of this program were: width= 7.5cm; height = 13.5cm; length = 50 cm. Dimension of column segments varied slightly as indicated in Table 1.

Table 1 – Experimental program

specimen number	column size dxhxL [cm]	longitudinal reinforcement sup / inf / grade	transverse reinforcement (hoops)	specific topic researched	anchorage detailing	reference
V31- v32, v33-v34	15x20x25	2d8mm 2d8mm A630-420H	A630-420H d2.5mm @2.5cm	velocity of deformation	hooks - development length in excess respecting ACI318	Ovalle, C (2004). [5]
v4-v8, v11-v15, V12-v16, v5-v7	9x15x25	2d8mm 2d8mm A630-420H	A630-420H d2.5mm @2.5cm	velocity of deformation	hooks - development length just minimum ACI318	Rojas, J [2009] [6]
A1-A2 G3-G4	10x30x50	2d8mm 2d8mm A630-420H	AT56-50 d4mm @2.5cm	velocity of deformation	straight - development length just minimum ACI318	Guzmán, A (2010, not yet published)
#1 to #8	10x30x50	2d8mm 2d8mm A630-420H	AT56-50 d4mm @2.5cm	velocity of deformation and detailing	straight and hooks. Development length just minimum ACI318 and shorter	Moreno,A (2012) [7]
v23, v24 v26-v27 v21-v30	10x30x50	4d8mm 4d8mm A440-280H	AT56-50 d4mm variable Spacing	velocity of deformation and detailing	straight ACI318. minimum length. Supplementary bars on beams	Vergara, M (2014) [8]
vc1-vc2 vc5-vc6	12x30x50	4d8mm 4d8mm A440-280H	AT56-50 d4mm inclined 45°	inclined transverse reinforcement	straight ACI318. minimum length. Supplementary bars on beams	Silva, B (2014) [9]
vcp1-vcp2 cp1 to cp4	12x30x50	4d8mm 4d8mm A440-280H	AT56-50 d4mm vertical and inclined 45°	inclined transverse reinforcement	straight ACI318. minimum length. Supplementary bars on beams	Pino, C (2016) [10]

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Specified concrete strength for all specimens was 350 Kgf/cm^2 on 200 mm cube. Steel of three different grades were used: A440-280H (f_y = 2800 kgf/cm^2) ; A630-420H (f_y = 4200 kgf/cm^2) and AT56-50 (f_y = 5000 kgf/cm^2).

AT56-50 4mm diameter bars were used for transverse reinforcement in most specimens. According to Chilean regulations, AT56-50 should not be used in elements subjected to seismic solicitation because its little strain hardening. However, after examining tested specimens of first two series of Table 1, constructed with the more difficult to get 2.5mm A630-240, it was found that this steel never yielded. This fact allowed the use of the widely available AT56-50.

3.2 Test setup

Previous work [5],[8], also showed that, even when at the beginning of tests, velocity of deformation does not influence results more than 10%, it does affect the way that specimens collapse. For this reason tests were performed at a velocity representative of the real earthquake. 5 Hz were used in the first two series of table 1, and 2 Hz were used in the following series. Loading program is shown in Fig. 3. A 10 min. pause was done between families of cycles. MTS controller added two or three cycles of lower amplitude, not shown in Fig. 3, every time the system was started or stopped.

Most test were filmed using a high speed camera NAC Hshot Mega working at 500 frames/sec.

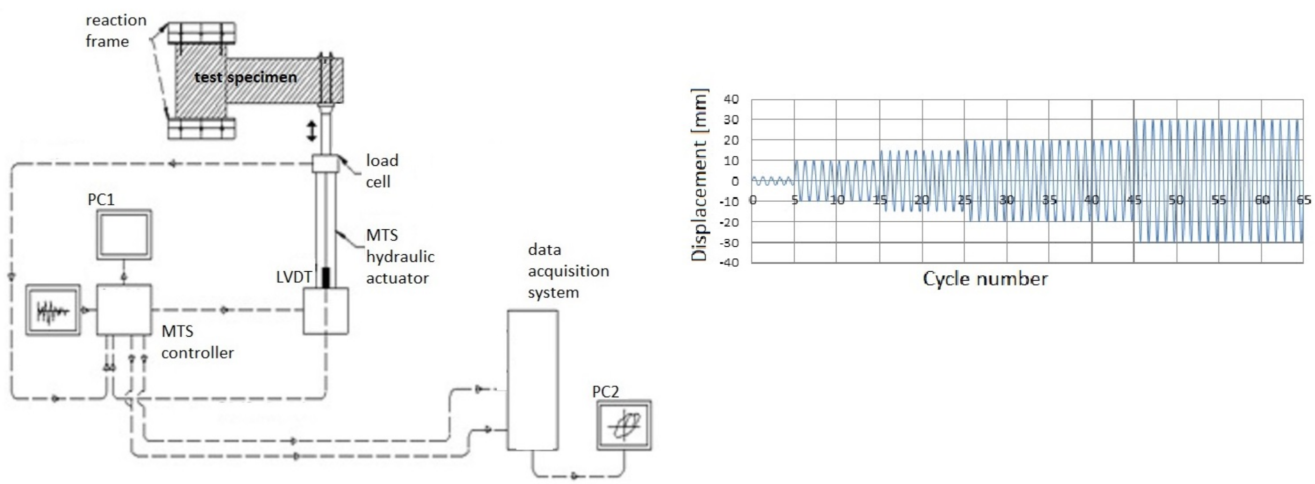


Fig. 3 - Test setup and typical loading program

3.3 Other details of tests specimens

Figure 4 shows the original specimen tested in first series of Table 1. In order to improve results of this first series two modifications to the distribution of reinforcement were considered:

- To extend length of plastic hinge zone and to move it away from the column, four short supplementary bars were added, as shown in Fig. 5. Steel grade was reduced from A630-420H (f_y = 4200 kgf/cm^2) to A440-280H (f_y = 2800 kgf/cm^2), to keep moment capacity of beams near the same value than before. Selected results of tests of one of these specimens are shown in figures 6 and 7.

- 45° (and 135°) inclined hoops were used for transverse reinforcement, instead of conventional 90° hoops, as shown in figures 8 and 9. Short supplementary bars mentioned before were also added. Selected results of tests of one of these specimens are shown in figure 10.

4. Test Results

Detailed results of tests of original specimens are given in references [5], [6] and [7], while results of tests of modified specimens are given in references [8], [9] and [10]. A summary follows.

4.1 Short supplementary bars

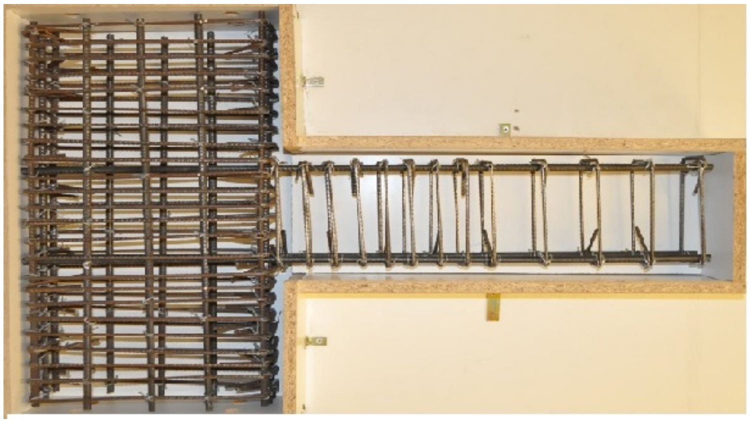


Fig. 4 Original specimen reinforcement [8]

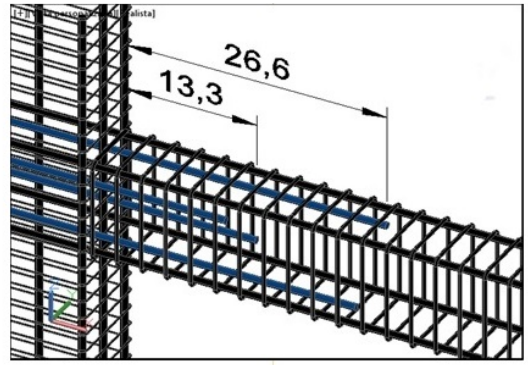


Fig. 5 Short supplementary bars added

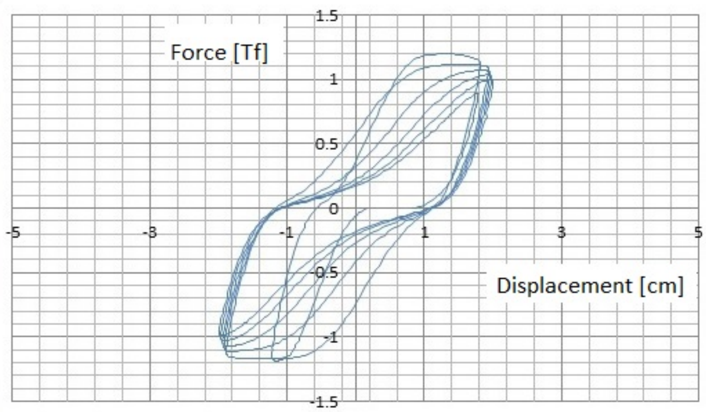


Fig. 6 External view of specimen v23 and hysteresis curve corresponding to the first series of cycles of 18 mm

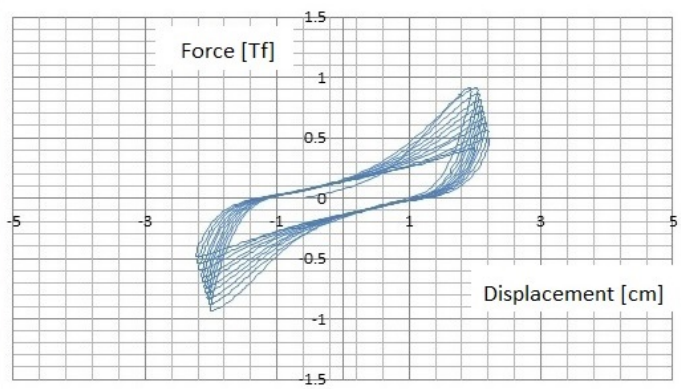


Fig. 7 External view of specimen v23 and hysteresis curve corresponding to the second series of cycles 18 mm

4.2 Inclined 45° hoops

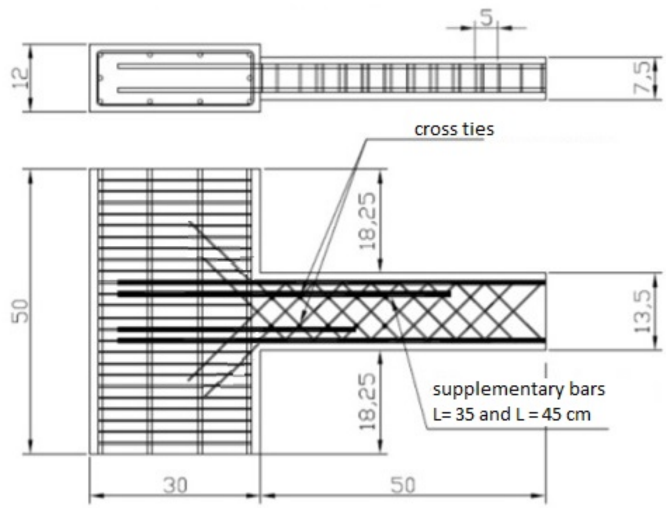


Fig.8 45° inclined hoops specimen (Adapted from [9])

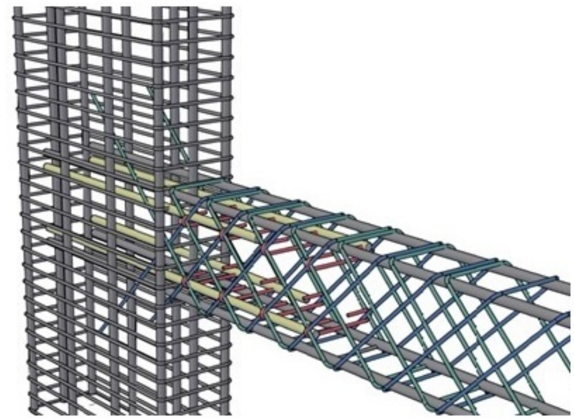


Fig. 9 Perspective view of reinforcement

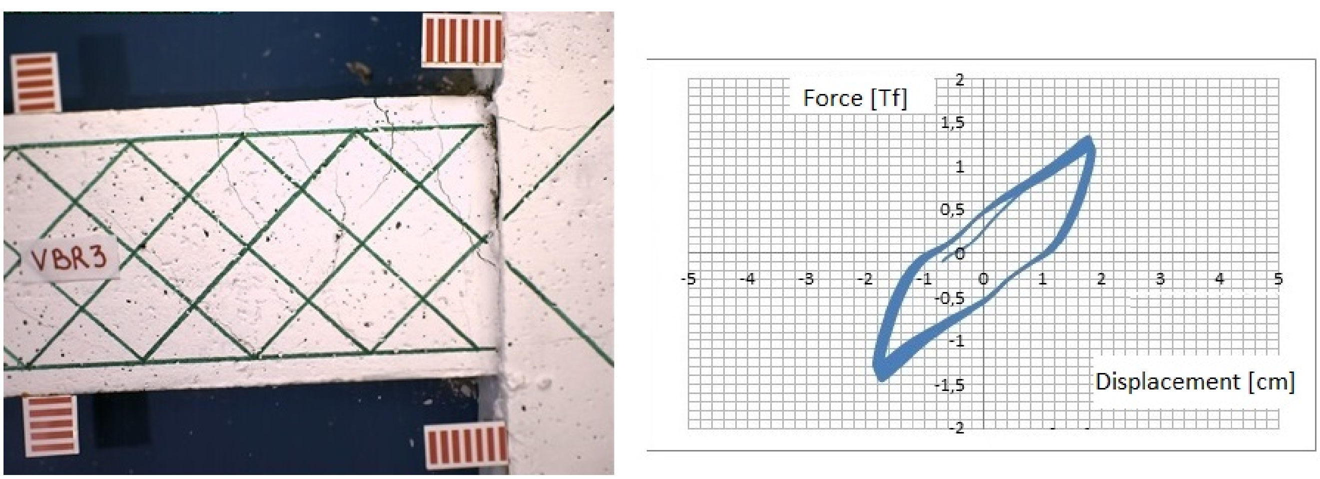


Fig.10 External view of specimen vBR3 and hysteresis curve corresponding to the second series of 18 mm cycles. More than seventy cycles with almost no degradation compares positively with results shown in Fig. 7.

4.3 Comments

Results shown in figures 7 and 10 are representative of specimens with 90 ° conventional hoops and 45° inclined hoops respectively. Actually, short supplementary bars did not change significantly strength or ductility of original specimens. They succeed in moving plastic hinges away from columns though, as Figs 6 and 7 show. Because results of tests of original specimens and those modified with short supplementary bars are similar, they are treated jointly in the analysis that follows.

Positive results of inclining hoops 45° were remarkable, in terms of ductility, stability of hysteresis curves, and strength. Fig. 10 shows that specimen VBR3, could have sustained cycles of 18 mm (4.5% drift) almost indefinitely, which is far from possibilities of conventionally reinforced concrete elements (Fig.8). Also, the maximum cycle load improved significantly respecting original specimens.

5. Data Analysis

Loading programs of specimens were equal until the first series of 18 mm amplitude only. For this reason, in order to compare their behavior, the accumulated ductility was taken as reference. This quantity was calculated as shown in Fig. 11 below:

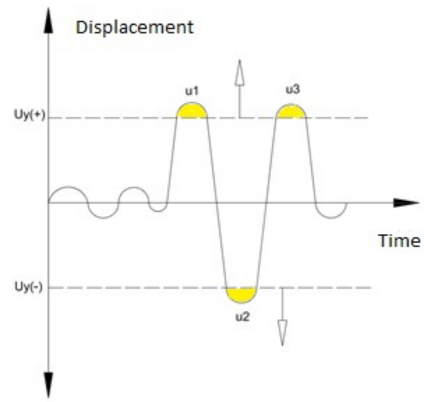


Fig. 11 Accumulated ductility [11]

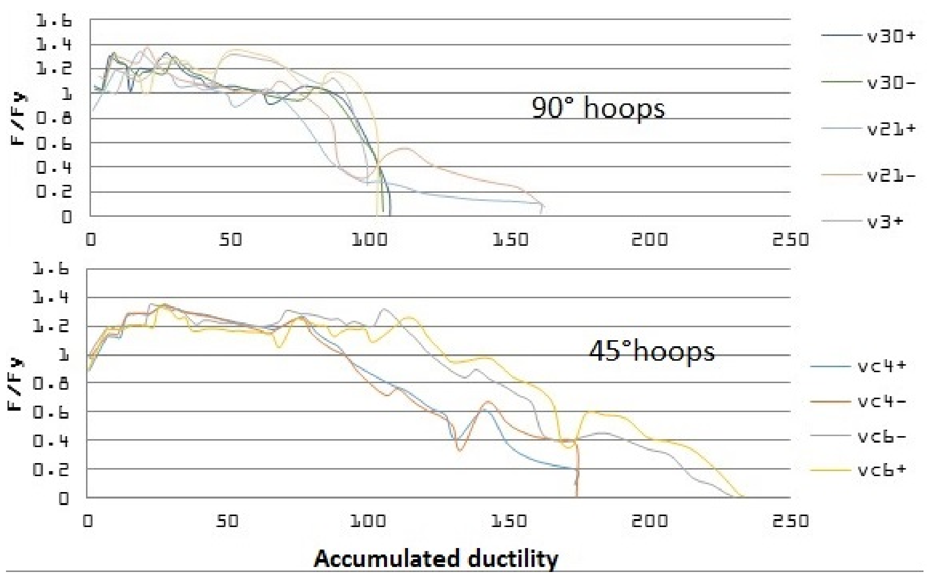


Fig. 11 Cyclic force amplitude versus accumulated ductility of selected specimens [11]

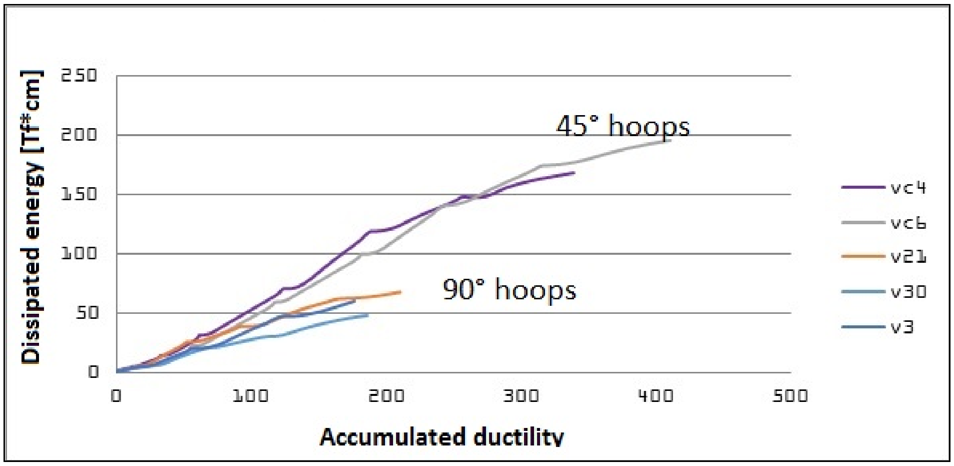
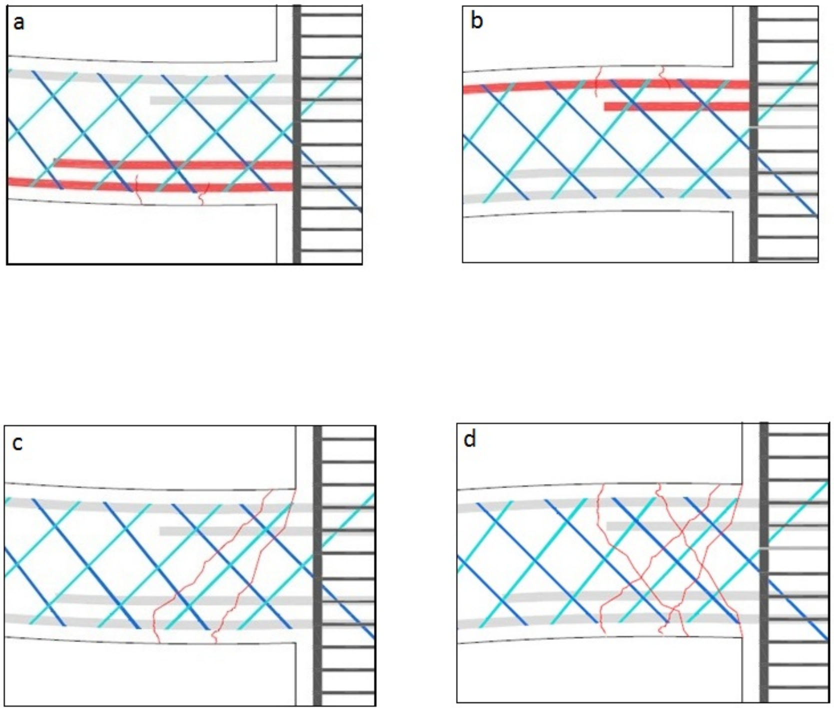


Fig. 12 Dissipated energy versus accumulated ductility for selected specimens (Adapted from [11])

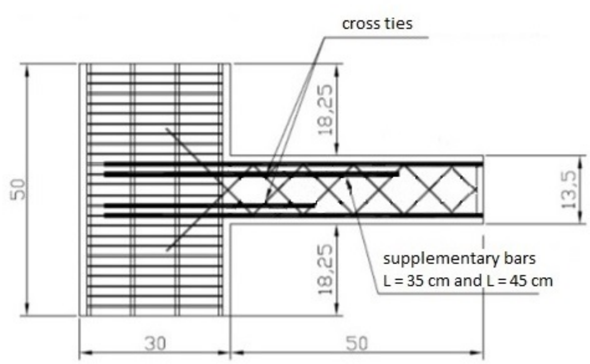
Figures 11, and 12 compares cycle force amplitude and dissipated energy v/s accumulated ductility for different specimens. From all curves it is clear the advantage of using inclined transverse reinforcement in beams. In the following pages the reasons for this favorable behavior are explained.

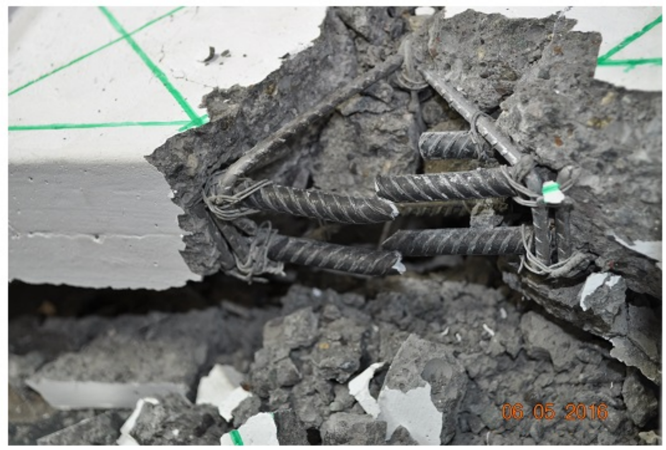
6. Further analysis



Figures 13 Sequence of cracking of an element with 45° inclined transverse reinforcement subjected to alternating increasing load. Picture (d) shows how concrete fragments results trapped by the reinforcement. (Adapted from [9])

Figures 13 a,b,c and d shows the sequence of cracking of an element with 45° inclined transverse reinforcement, as those described in this report, subjected to an alternating increasing load. During the first stages of the test, flexural cracking is observed only, pictures (a), (d). After load increases shear cracking appears, pictures (c) and (d), forming a net of concrete fragments. It was observed during tests that inclined shear cracks usually progress following a 45 deg. inclined line between two stirrups. Thus, concrete fragments are "trapped" by two perpendicular inclined stirrups, and integrity of the element is maintained for a while. On the contrary, fragments are free and escape rapidly through spaces left by conventional 90° stirrups.





Figures 14: Inclined transverse hoops are not convenient for elements with low transverse reinforcement

However, inclined transverse reinforcement has some drawbacks. Beginning: for the same amount of hoops, they are longer and pitch is twice of conventional 90° hoops. Thus, tendency of buckling and fracture of main reinforcing bars in elements with low transverse reinforcement is noticeable, as Figs 15 show. Furthermore, inclined hoops have a tendency to slip after concrete cover is lost, as shown in figure 16. Thus, they need to be effectively tied to the longitudinal bars. Welding, if possible, is desirable. Finally, for the same reason, a pair of 45° and 135° hoops should be tied together. Fig. 16 shows an especially bad way of configuring transverse reinforcement.

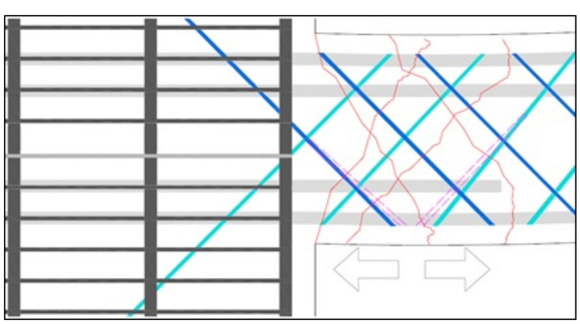


Fig. 16 Tendency of slipping of inclined transverse reinforcement

7. Conclusions

Advantages of 45° inclined transverse reinforcement are evident in terms of strength, ductility and its ability for keeping integrity of beam elements during a destructive earthquake. It was shown that beam elements with inclined transverse reinforcement can sustain cycle deformations of 4.5 % drift almost indefinitely. However, they need to be carefully designed and constructed, otherwise catastrophic failure could occur due to buckling and fracture of main reinforcing bars.

8. Acknowledgements

Students of the Construction program at UTFSM- Civil Engineering Department built carefully all test specimens. Thanks to all of them for saying that 45° transverse reinforcement is not particularly difficult to build. Thanks also to Gerdau Aza, who paid for some of the expenses of the test system.

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