EXPERIMENTAL STUDY ON YIELD DISPLACEMENT OF A RC BEAM WITH SLAB SPECIMEN USING HIGH STRENGTH REBARS

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Abstract

The study has been carried out to understand the performance of beam with slab specimen as a monolithic or composite structure. These studies are useful in defining the yield point and understanding the contribution of slabs. The concept of effective width has been used in RC standards to evaluate the contribution of a slab to the beams in terms of stiffness and moment of resistance. Stiffness degradation coefficient after cracking is also affected by effective width consideration. The contribution of stiffness and moment capacity has to be quantified. A precise definition of yield deformation is very significant in the context of seismic loads and seismic performance of an RC structure. Therefore, accurate prediction of yield deformation is required. Since, the yield point is characterized by significant energy absorption therefore energy absorption is also a good index to define the yield point of RC structures. Therefore in this study contribution of slab to stiffness and moment is obtained along with the use of energy absorption to define yield point.

Keywords: RC beam-slab; Load-displacement; yield point; component contribution; energy absorption

1. Introduction

The yield point characterizes the seismic performance of a structure. As the yield point is characterized by significant energy absorption. Therefore, several studies are carried out to understand the flexural behavior of the flexural members such as a beam. Therefore load-displacement is a good index for measuring the seismic performance of the structures. Since the slab affects the flexural performance of the beam, RC standards have provisions for the partial contribution of the slab [1].

This study is focused on the flexural performance of the RC beam with slab under static cyclic load. It focuses on the contribution of the slab to the flexural behavior of the beam. Huge stubs are used to provide actual restraint conditions. In this study firstly load-displacement is studied followed by crack patterns, rotation and displacement along with the height. The impact of the slab over beam performance is studied through its contribution to the stiffness and capacity. The yield point has been defined through energy absorption also.

2. Experimental outline

2.1. Specimen outline

The test specimen is a composite structure of two large beams, a sub-beam and slab as represented in Fig 1. High strength rebars are used for large beams. The specimen was loaded after underwater curing of 100 days.

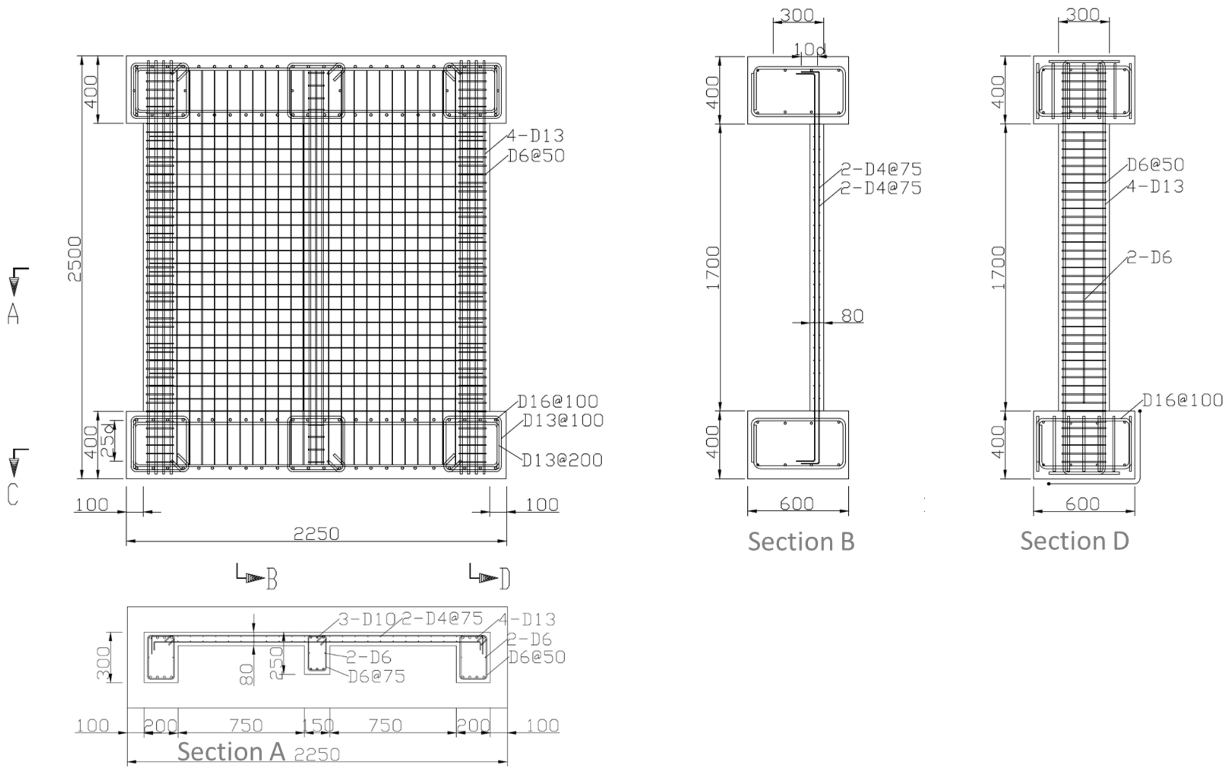

Figure 1: Specimen outline

2.2. Loading arrangements

The specimen was loaded for 17 cycles with the first three cycles load controlled and then the rest were displacement controlled. The loading cycle followed the following steps ±10 kN, ±20 kN, ±30 kN, ±1/2000, ±1/1000, ±1/400 (2 cycles), ±1/200 (2 cycles), ±1/133 (2 cycles), ±1/100 (2 cycles), ±1/50 (2 cycles) and ±1/25 (2 cycles). In this study positive loading is referred to as the load applied outwards to the plane of the slab as represented by a blue arrow in Fig. 2. For positive loading slab at the bottom is in compression and slab at the top is in tension and vice versa for negative loading.

2.3. Measurement details

Moment distribution along the height varied linearly from the top (maximum +ve or -ve) to bottom (maximum +ve or -ve). Some strain gauges were attached at the top and bottom of the specimen as shown in Fig. 3. Displacement gauges were used to measure the vertical displacement on both sides of the specimen which can be used to calculate the rotation and bending displacement of the specimen.

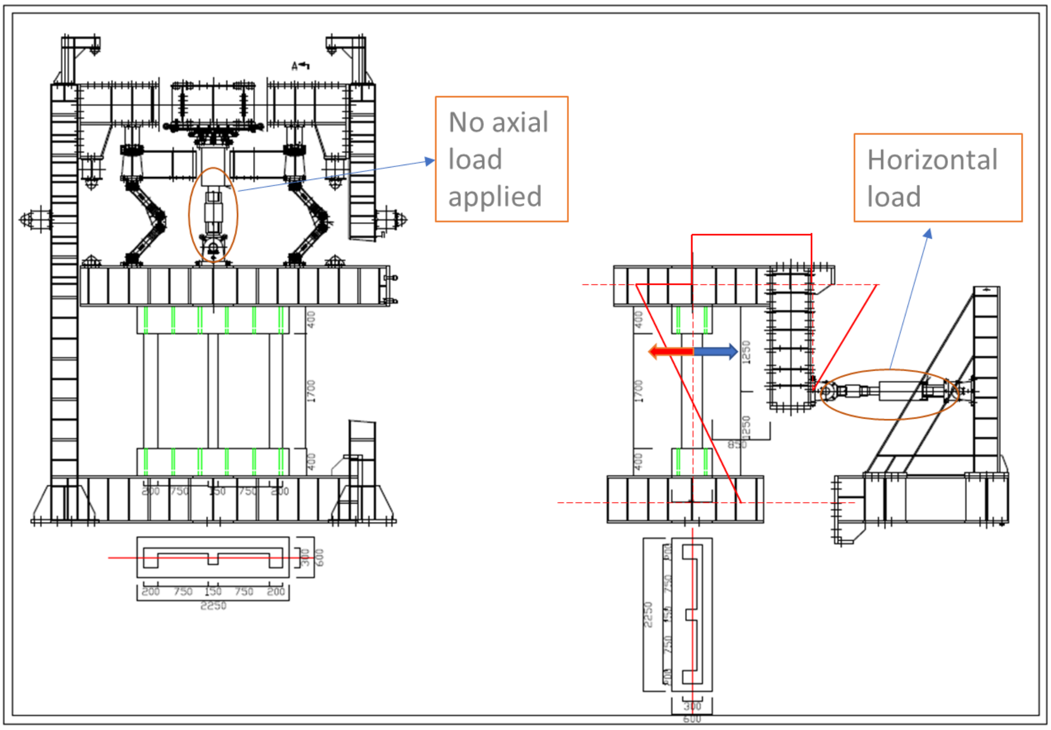

Figure 2: Loading arrangements

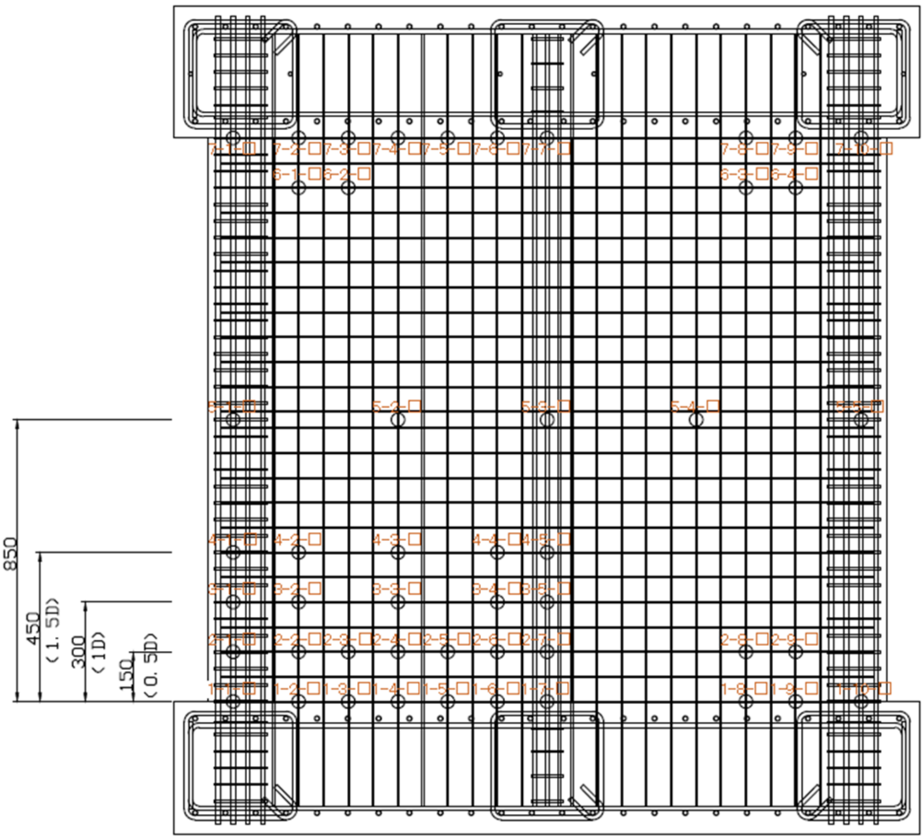

Figure 3: Strain gauge distribution

2.4. Material property

(1) Reinforcing materials

The material properties by direct tensile tests for the four types of rebar used are summarized in table 1.

Table 1: Reinforcement details

	Location	Steel type	f_y (MPa)
D4	Slab	SD345	357
D6	Stirrups	SD345	420
D10	Sub-beam	SD345	360
D13	Large beam	SD545	545

(2) Concrete

The property test for concrete which includes compressive strength, split tensile test and fracture energy test was carried at the time of loading test. The specimen used for property tests were as per RC standard. The compressive strength and tensile strength (at age of 100 days) however show deviation from 28-day strength (27 MPa) to be equal to 30 MPa and 2.5 MPa respectively.

2.5. Load-displacement simplified calculation

The capacity of the specimen is calculated assuming that both layers of rebar of the slab contribute to the total capacity when the slab is in tension and the neutral axis is a straight line. The capacity at the crack, yield and ultimate failure are evaluated as per AIJ standards [1] as shown in the equations. The capacity of the specimen when the slab side is in tension includes the contribution of the large beam, sub-beam and slab. When the slab side is in compression the capacity of the specimen is contributed only by the large beams and sub-beam. Stiffness degradation coefficient (αy) [1] is used for obtaining the effective stiffness of the specimen after cracking. The calculated load-displacement relationship is shown in Fig. 4 with the reddish-brown line.

$$\sigma_{cr} = 0.6\sqrt{f_{ck}} \tag{1}$$

$$M_{cr} = \sigma_{cr}\frac{I}{y} \tag{2}$$

$$M_y = \frac{7}{8} \times a_{st}\sigma_y \times d \tag{3}$$

$$M_u = 0.9 \times (a_{st}\sigma_y \times 1.1) \times d \tag{4}$$

Where σ_{cr}, f_{ck}, σ_y, I, y, M_{cr}, M_y and M_u are the stress of concrete at crack characteristic strength of concrete, characteristic strength of steel, Inertia, depth of outermost fiber from the neutral axis, moment capacity at the crack, yield and at failure.

3. Test results

3.1. Load-displacement relationship

The load-displacement relationship is represented in Fig. 4. The yielding of slab rebars started at 1/400 whereas large beam rebars (high strength rebars) yielding starts at 1/133. All the rebars yielded at 1/75. But the loading cycle of 1/75 was not considered during loading tests. The yield capacity from test results is comparatively higher in comparison to the calculated capacity. As per the calculation the assumed neutral axis is close to the slab. But for loading test results the neutral axis is at more distance for large beam as compared to the calculation. Hence, the capacity of large beam increased thereby also increasing the capacity of the specimen.

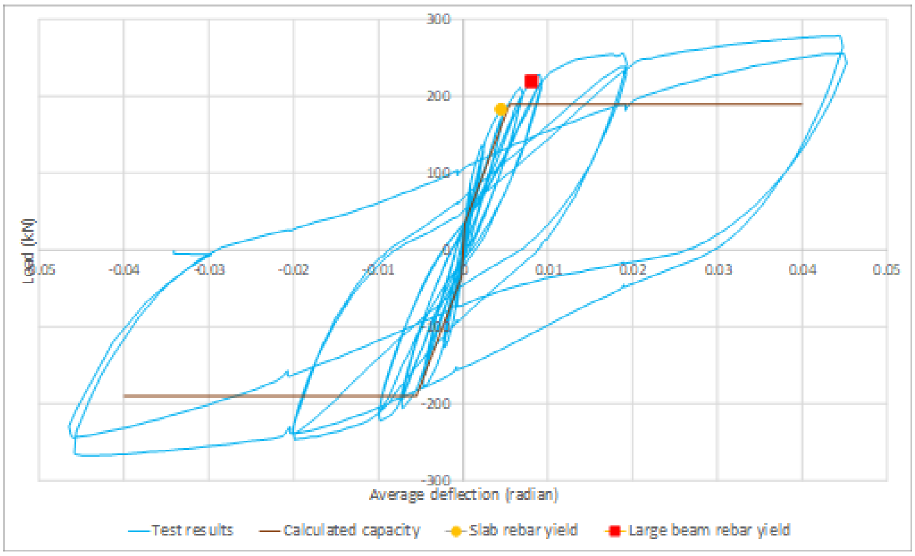

Figure 4: Load-displacement relationship

3.2. Crack patterns

The cracks observed are mainly flexural cracks and are concentrated at the top and bottom of the specimen. Moments at top and bottom are maximum for any applied horizontal load as discussed in the previous sections. The cracks represented with green, blue and red color are initial cracks, cracks due to positive loading and negative loading respectively. On the slab side of the specimen the cracks for positive loading are concentrated on top while for negative loading at the bottom of the specimen. These cracks are because the surface is in tension which results in cracking. On the beam side of the specimen cracks are observed at both ends of the specimen for positive and negative loadings. This mixed crack pattern is observed due to the shifting of the neutral axis into the slab. The depth of the neutral axis is such that the slab part on the east side of the specimen is in tension for both loading conditions. Therefore, cracks are observed for both positive loadings as well as negative loading. The crack patterns for the loading cycle of 1/25 are shown in Fig. 5. After yielding the cracks extend in length and expand in width with each loading cycle. Diagonal cracks were also observed for both loadings. It is due to bulging out of the slab. Cracks are observed up to a height of 2D, where D is the depth of beams.

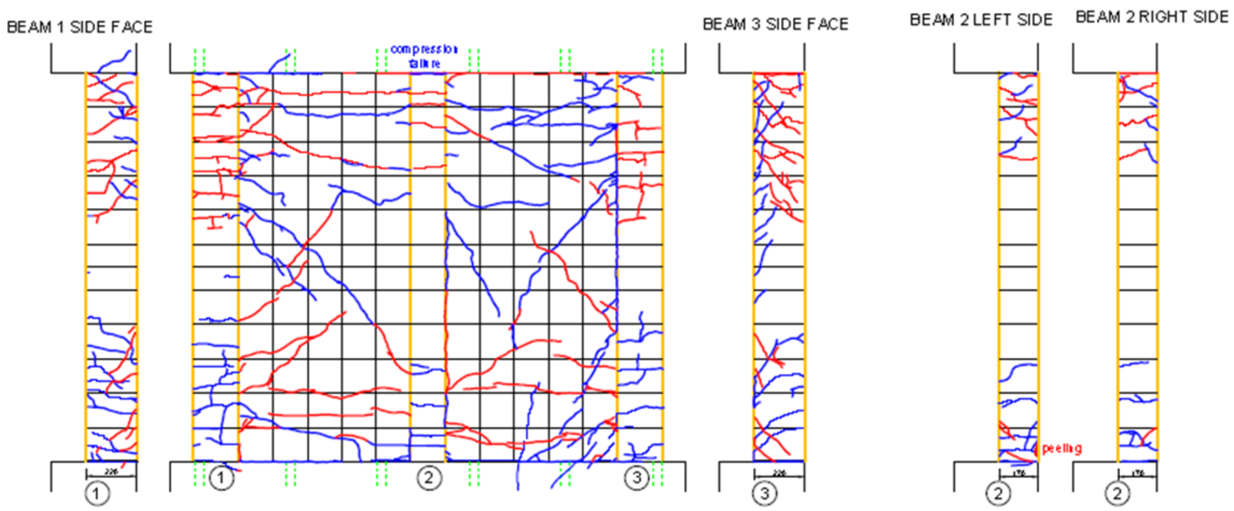

Figure 5a: Crack patterns (beam side)

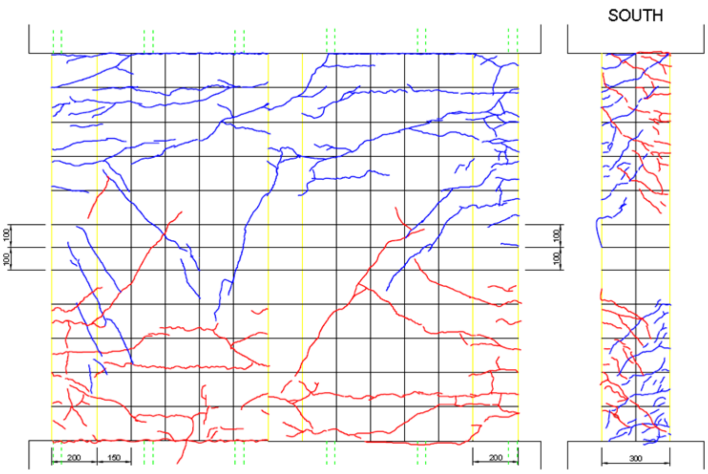

Figure 5b: Crack patterns (slab side)

3.3. Rotation along with the height and flexural displacement

Vertical displacement was measured for the beam side and slab side of the specimens using displacement transducers as discussed in section 2.3. Segmental (local) rotation is obtained by dividing the difference of vertical displacements by horizontal distance between corresponding transducers. The rotation of specimen along with the height is shown in Fig. 6.

Flexural displacement is obtained by integration of rotation along with the height assuming constant curvature for each segment. The flexural displacement for each loading cycles is represented in the Fig. 7. The flexural displacement calculated is about 83% of total horizontal displacement at the yielding of large beam rebar (11.34mm / 13.63mm). Therefore, the dominant displacement is flexural displacement.

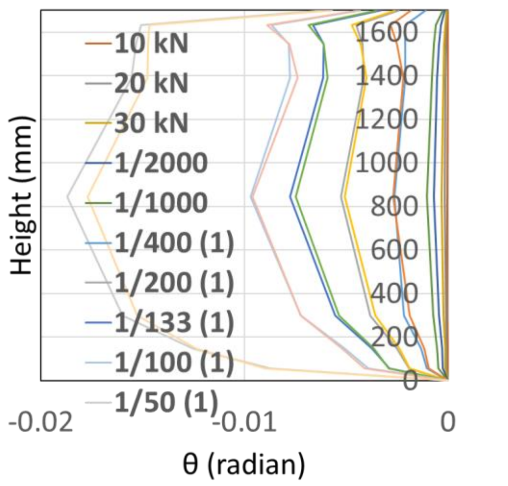

Figure 6: Rotation along height

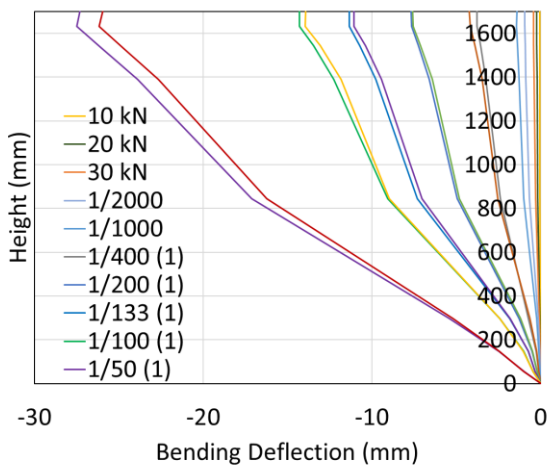

Figure 7: Bending deflection

3.4. Curvature distribution along the width

The curvature distribution along the width of the specimen is represented in Fig. 8 for slab in compression but this pattern is equally true for slab in tension also. It is observed that strain in slab rebars is higher as compared to that of beam rebars. These strain values from both sides of the specimen are used to calculate the curvature for any given section by the equation shown below. The curvature distribution represented in

Fig. 8 is for the bottom section of the specimen. It is evident from it that the curvature of the slab part is higher in comparison to the large beam. The bulging of the slab contributed to the higher curvature. The distribution pattern for curvature along the width of the specimen is similar for slab in tension as well as a slab in compression.

$$Curvature\ (\emptyset) = \frac{\varepsilon_1 - \varepsilon_2}{d_s} \tag{5}$$

Where, $\varepsilon_1, \varepsilon_1$ *and* d_s are strain of rebars on both sides and distance between the rebars.

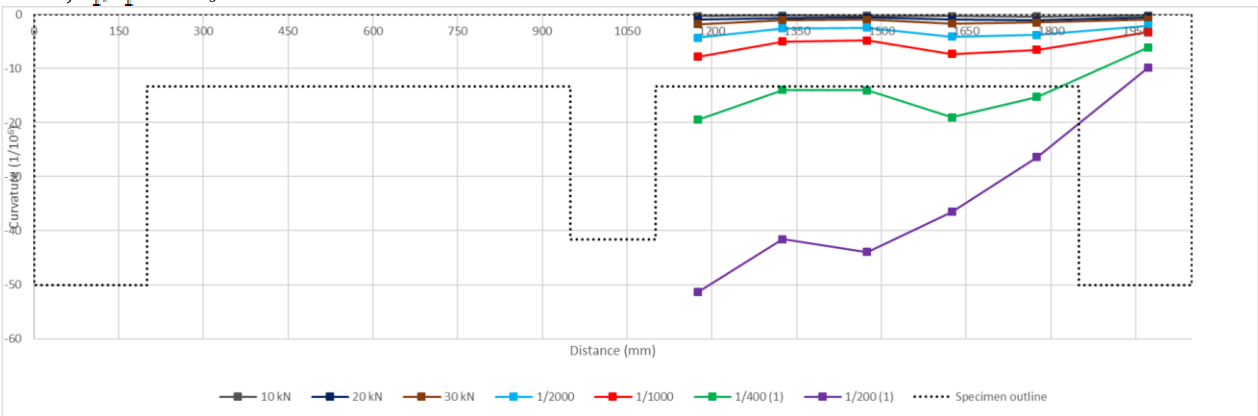

Figure 8: curvature distribution (slab in compression)

4. Contribution of each component

4.1. Stiffness contribution

The specimen has not a regular cross-section i.e. it is not a plane rectangular beam therefore total stiffness is the sum of the stiffness contribution of each component (large beams, sub-beam and slab). The stiffness is calculated through the following steps. Given data: strain values (ε_1 & ε_2) on both sides of the specimen (slab side and beam side).

Step 1

$$Neutral\ axis = \frac{\varepsilon_1 \times d}{\varepsilon_1 + \varepsilon_2} \tag{6}$$

Step 2

$$I_c = I_a + I_b \tag{7}$$

$$I_{a\ or\ b} = \frac{bh^3}{12} + A \times \left(\frac{h}{2}\right)^2 \tag{8}$$

$$I_s = n \times (\pi \frac{\pi D^4}{64} + a_{st} \times (NA - cover)^2) \tag{9}$$

Step 3

$$Total\ stiffness\ (EI) = E_c I_c + E_S I_s \tag{10}$$

Where, ε_1 and ε_2 strain values of rebar on both sides of the specimen, d is effective depth, b=width of the section, h is the depth of the assumed section above or below the neutral axis, A is the area of section = bh,. I_c, I_a, I_b, and I_s are the second moment of area about a neutral axis for concrete sections, above and below the neutral axis and rebars. E_c and E_s are Young's modulus of concrete and steel respectively.

The contribution of stiffness from each component is represented in the Fig. 9 and Fig. 10 for slab in tension and compression respectively. The contribution of concrete in tension zone after cracking is neglected in this stiffness calculation. Effective stiffness for rebars after yielding is obtained as secant stiffness at that strain from the stress-strain relationship of the given rebars. Stiffness of the specimen and its component is represented in the Fig. 9 and Fig. 10 for slab in tension and compression respectively. Stiffness represented for the large beam is the sum of the stiffness of two large beams. Stiffness of slab is the sum of the stiffness of both slabs.

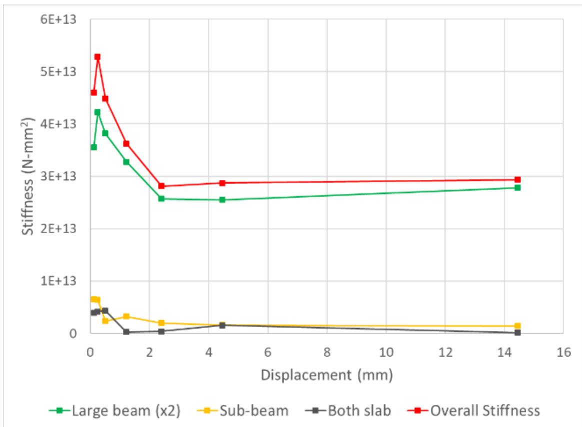

Figure 9: Stiffness contribution (slab in compression)

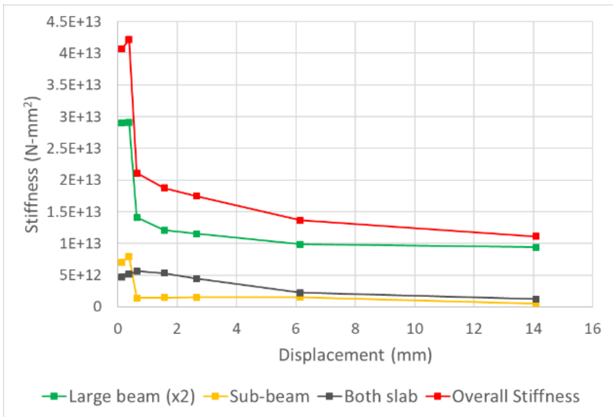

Figure 10: Stiffness contribution (slab in tension)

4.2. Moment contribution

The contribution of each component refers to the share of the capacity of beams and slab to the total capacity of the specimen. The individual capacity as per calculation for the large beam is 125 kN-m, for sub-beam is 13.9 kN-m and 183.8 kN-m is the yield capacity of specimen therefore contribution of the slab is 44.9 kN-m. The sectional contribution from the specimen is represented in Fig. 11 and Fig. 12. Strain values are used to obtain the contribution of each component. Firstly, strain from both sides of the specimen is used to calculate curvature as described in section 3.4 the depth of the neutral axis and stiffness is calculated as discussed in section 4.1. The moment capacity is obtained as the product of stiffness and curvature as shown in the equation below.

$$Moment\ (M) = EI\emptyset \qquad (11)$$

The contribution of each component i.e. large beams, sub-beam and slab is shown in Fig. 13 and Fig. 14. It is observed that for slab in compression significant contribution from each component is obtained. But for slab in tension almost all the capacity is due to the large beams (approximately 90%). The calculated load capacity of the specimen is compared with the test results and is represented in Fig. 15. For higher displacements the calculated load is higher. It is due to the fact that the Youngs modulus for concrete is not modified for higher displacements. Youngs modulus of concrete for higher displacements is reduced considerably therefore the calculated capacity will be lower.

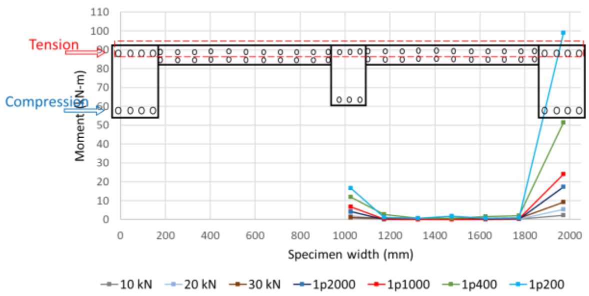

Figure 11: Moment distribution (slab in tension)

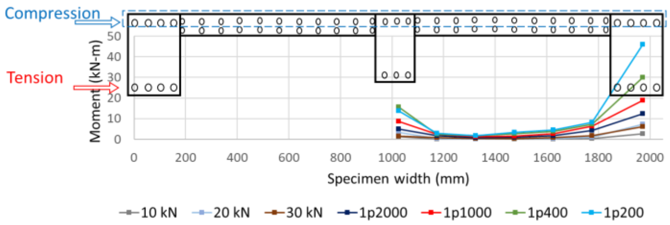

Figure 12: Moment distribution (slab in compression)

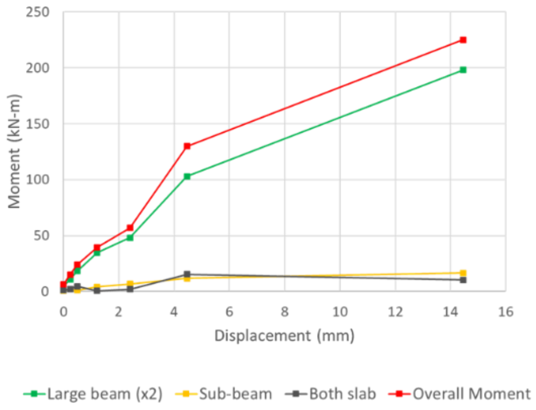

Figure 13: Moment contribution (slab in tension)

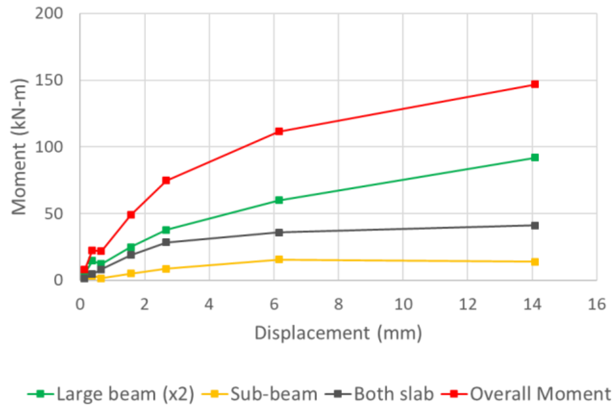

Figure 14: Moment contribution (slab in compression)

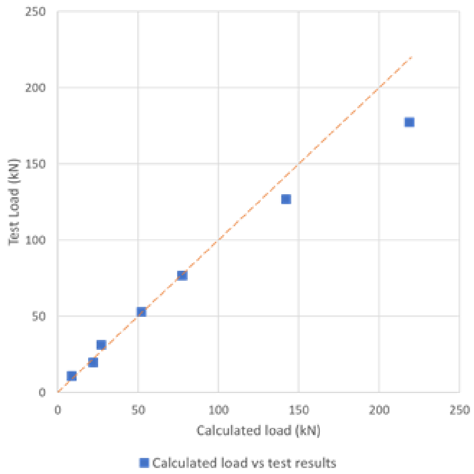

Figure 15: Test load vs calculated load

5. Energy absorption

The energy imparted to any structure is dissipated within the structure. The dissipation of energy is an important characteristic that defines structural performance under seismic loading. The Fig. 16 and Fig. 17 represents the energy absorption and equivalent damping coefficient respectively. As it is observed that there is no significant change up to a cycle of 1/100. But from the test results, it is observed that all rebars yielded at a displacement of exactly at 1/75. From 1/100 to 1/75 no unusual event is observed, and load increases linearly with displacement upto this point. So, it can be concluded that the yielding of the specimen is between 1/100 and 1/50. The slab rebars and sub-beam rebar started yielded at 1/133. Large beam rebars yielded at 1/100. Therefore, to define the yielding point of the specimen yielding of the large beam should be focused.

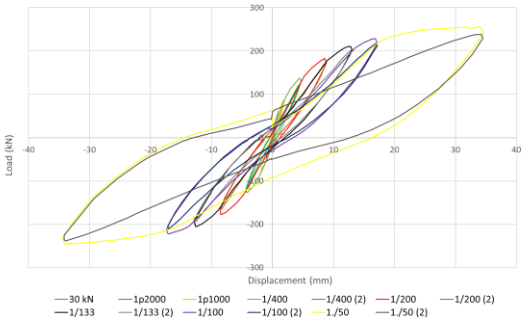

Figure 16: Energy absorption

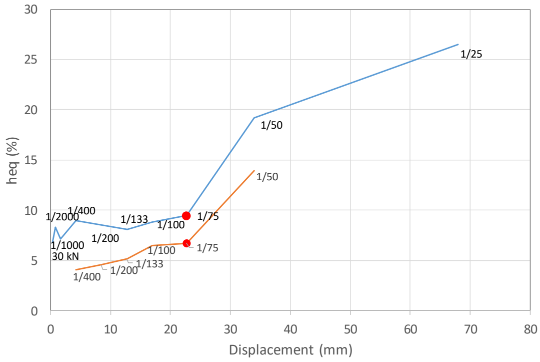

Figure 17: Equivalent damping coefficient

6. Conclusions

The conclusion drawn from this study include Crack patterns are affected by depth of neutral axis which can result in mixed crack patterns. The dominant displacement is flexural displacement with majority of flexural cracks. The depth of neutral axis also defines the contribution of components to the stiffness and capacity. Major contribution is of large beam for stiffness and capacity. for slab in tension, slab affects the stress distribution thereby increasing the capacity. while for slab in tension negligible effect can be observed for stress distribution from slab to beam. This means that for slab in tension all the compressive stress is taken by large beams. The significant change in energy absorption observed after yielding of large beam rebars. Therefore, to obtain yielding point of the specimen large beams shall be focused.

7. Acknowledgement

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8. References

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