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Seismic resistance of fiber-reinforced slab-column connections

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ABSTRACT: The effect of fiber-reinforcement on the seismic performance of slab-column connections was investigated experimentally. Three half-scale interior and exterior connections were tested under simulated earthquake-type loading. The fiber reinforcement consisted of ductile low carbon steel with a minimum specified tensile strength of 345 MPa and were deformed with an aspect ratio of 60. The amount of fiber reinforcement was varied from 30 to 90 kg/m^3 of concrete. The addition of fiber reinforcement greatly improved the energy dissipation capacity and increased the ductility of all specimens. It also enhanced the shear capacity of the interior connections but did not affect the shear strength of exterior connections. A smaller fiber content had no effect on the failure mode of the interior connections but the mode of failure changed from punching to that of flexure with increased fiber content. The test results suggest an optimum fiber content of between 30 and 60 kg/m^3 of concrete for improved seismic resistance.

1 EXPERIMENTAL PROGRAM

Six on-half scale interior and exterior slab-column connections were tested to study the effect of fiber reinforcement on the behavior of connections under simulated earthquake-type loading. The column in each specimen extended to the story mid-height where the moment was assumed zero and the slab was terminated at mid-span where the moment from lateral load is also assumed zero. Each specimen was cast in an upright position, and both the slab and the column were cast in a single operation. The specified concrete strength for all specimens was 27.5 MPa. The steel reinforcement in all specimens consisted of Grade 60 steel (413.7 MPa minimum yield strength).

The main variable of this investigation was the fiber reinforcement ratio, measured in kg/m^3 of concrete. The fiber reinforcement was made of ductile low carbon steel with a minimum specified tensile strength of 345 MPa. The fibers were deformed with a length of 25 mm and aspect ratio of 60. A pair of interior and exterior connections was tested for fiber contents of 30, 60, and 90 kg/m^3 of concrete. Further detail about specimens is given in Table I

Fiber reinforced concrete was placed only in the slab-column connection region including the joint portion of the column and a surrounding area of slab having a radius of approximately 1.2 m around the column. The remaining slab and column portions, away from the critical connection region, were made of non-fiber concrete. The overall configuration of the specimens is shown in Fig. 1.

Each specimen was reinforced with the same amount and distribution of steel and their design was

Table 1: Test specimen detail

Specimen name	Fiber ratio kg/m^3	Plain concrete strength MPa	Fiber concrete strength MPa
Int_90	90	34.5	42.3
Int_60	60	36.8	31.7
Int_30	30	39.0	37.6
Ext_90	90	34.5	42.3
Ext_60	60	36.8	31.7
Ext_30	30	39.0	37.6
Int_0	0	34.9	-
Ext_0	0	34.9	-

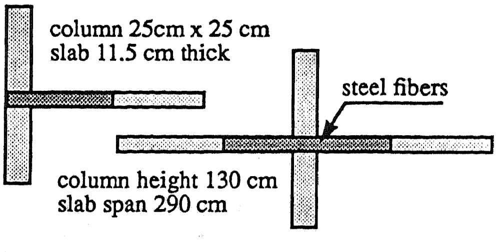

Figure 1 Specimen Configuration

based on the current flat-plate design procedures (ACI 318-89). During each test, the specimens were loaded with full gravity dead load plus 30% of the design live load to simulate the service load condition. The lateral loading routine was applied to the top of the column while the reactions were measured at he slab edge supports and at the base of the column. The loading routine which consisted of several cycles of increasing lateral displacements is shown in Fig. 2. To evaluate the stiffness and strength degradation of the specimens, small displacement cycles of 0.75% drift were added in between major displacement cycles.

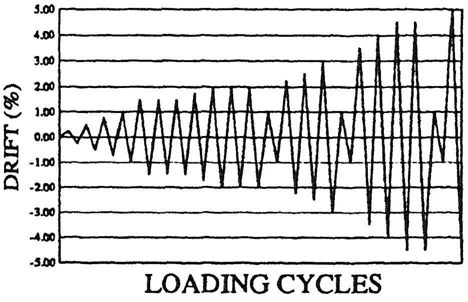

Fig. 2 Loading Routine

2 DISCUSSION OF RESULTS

The observed response of the interior and exterior connections is discussed with respect to their mode of failure, lateral load vs. drift response, strength, stiffness degradation, and ductility during the application of the loading routine. Further details of the test results can be found elsewhere (Diaz & Durrani, 1991).

2.1 *Failure mode*

The failure mode of the specimens provided an interesting insight on the effect of fiber reinforcement on their behavior. The interior connections, Int_90 and Int_60 experienced a flexural mode of failure. These specimens were able to maintain their strength through the end of the test. The specimen Int_30, which had the smallest amount of fiber, failed in punching shear at the connection. The control specimen, Int_0 (Robertson & Durrani, 88, 91), which had no fiber reinforcement, also experienced a punching shear type of failure. This change in the failure mode suggests a beneficial effect of using fiber reinforcement in interior slab-column connections. Since the change in failure mechanism occurred at fiber content between 30 and 60 kg/m^3 of concrete, it may be inferred that the optimum fiber content is in between these two ratios with 60 kg/m^3 being a conservative value.

None of the exterior connections exhibited a clear failure mode. Furthermore, they maintained the maximum load through the end of the test. The specimen Ext_50, however, showed a significant reduction in energy dissipation per cycle at higher drift levels. Based on the failure mode observations, it may be concluded that neither the presence or absence of fiber reinforcement nor the amount of fiber made any significant difference in the failure mode of exterior connections. As such, the fiber reinforcement was not as effective in exterior connections as it was in the interior connections.

2.2 *Load-drift response*

The load-drift response shows the total horizontal load applied to the top of the column against its displacement expressed as a percentage of the column height, referred to as drift. The load-drift response of interior connections was approximately linear up to 1% drift and as the drift increased to 2%, the deformation began to increase faster than the increase in load indicating a gradual loss of stiffness. The loss of stiffness continued until the specimens reached the peak load, which generally occurred at about 4.5% drift. The specimens Int_90 and Int_60 retained 90% of the peak load through the end of the test. The strength of the interior connections appears to be affected by the presence of fibers but not by the amount of fiber. The fiber reinforced interior connections resisted a higher peak load than the connection without fibers. Overall, the load-drift response of interior connections for fiber contents of 60 and 90 kg/m^3 were very much similar, suggesting that the amount of fiber in excess of 90 kg/m^3 did not improve the response any further. With a fiber content of 30 kg/m^3, the deterioration of the response and the ultimate punching failure of the interior connection could not be prevented.

The load-drift plots of exterior connections were generally similar in shape to those obtained for the interior connections. However, the response of exterior connections is characterized by different peak loads and rate of strength loss in the two loading directions. The difference in strength in the two loading directions is attributed to the presence of the gravity load on the slab and the difference in the flexural strength of the slab in positive and negative bending. Since none of the exterior connections exhibited any significant differences in their behavior, the effect of the presence or the amount of fiber content on the response of exterior connections may be considered minimal.

2.3 *Strength*

The strength envelope of all the interior connections, including the reference specimen which did not have any fiber reinforcement is shown in Fig. 3. Fiber and non-fiber interior connections had similar strengths at drift levels below 2.0%.

Beyond this drift level, however, the fiber reinforced specimens displayed a higher strength and this trend continued until 4% drift. The non-fiber specimen failed between 3.5% and 4.0% drift with a sudden loss in its load capacity. Fiber reinforced specimens, on the other hand, continued to carry loads without significant reduction in capacity upto 6% drift. Neglecting the variation in concrete strength, the mere presence of fibers appears to increase the strength of interior connections by 24% to 39% of the non-fiber reinforced specimen strength. In the presence of fibers, the peak load also occurred at higher drift levels.

The strength envelopes of the exterior connections are shown in Fig. 4. It is interesting to note that the overall load capacity of the fiber reinforced specimens is not much greater than that of the plain concrete specimen. Even though the presence of fibers is expected to enhance the tensile and thus the shear strength of the concrete matrix, the fiber reinforcement did not increase the load capacity of the exterior connections, suggesting that the load capacity of the exterior connections is limited by torsion of the slab edge which is not improved by the presence of the fibers. The behavior of specimen Ext_60 was the closest to the ideal behavior of an exterior connection, considering that the reduction in load was minimal at large drift ratios.

2.4 *Stiffness*

The stiffness of specimens during a cycle was defined as the average of the secant stiffness corresponding to measured maximum positive and maximum negative peak loads. The fiber reinforced interior connections in general had a higher initial stiffness compared to the non-fiber specimen. As the drift level increased, the stiffness of the three interior connections converged together despite the different amount of fiber reinforcement ratios, but their stiffness remained higher than the stiffness of the plain concrete specimen. The stiffness of Int_30 dropped toward the end of the test due to the onset of the punching failure. The overall higher stiffness of Int_30 compared to other fiber specimens may be attributed to the density of the fiber in the concrete matrix. Higher concentration of fibers may result in weaker bond with concrete and, therefore, a higher percentage of fibers fail in pull out instead of yielding. In contrast, low concentration of fibers may result in stronger bond with concrete, which results in higher percentage of fibers to reach their yield strength. The amount of fiber therefore appears to be an important parameter affecting the stiffness of connections.

The addition of fiber reinforcement did not have any appreciable effect on the stiffness of exterior connections. However, it is observed that the stiffness for all exterior connections converged to the same low stiffness at large deformations toward the end of the loading history. Differences in stiffness are noticeable at lower drifts, but the tendency of these differences to disappear after some cycles reveals that at failure, the stiffness of fiber reinforced exterior connection with any fiber content could be the same as that exhibited by a non-fiber connection.

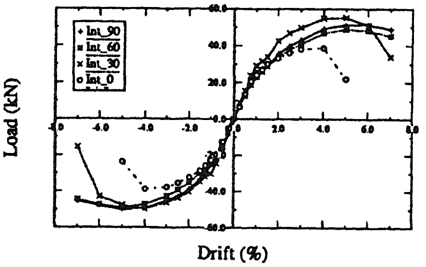

Fig.3 Load-drift envelope of interior connections

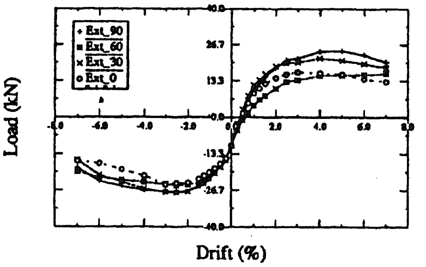

Fig. 4 Load-drift envelope of exterior connections

2.5 *Ductility*

Ductility is a desirable property for connections subjected to load reversals as during an earthquake. For comparison purposes, the ductility of connections is defined as the ratio of maximum drift during a given cycle to that at first yield of the slab reinforcement. The ductility of Int_0 at peak load and at 5% drift was about 1.2 times the ductility at 1.5% drift. In contrast, the ductility of specimens Int_30 and Int_60 at peak load was approximately 2.3 times the ductility at 1.5% drift. Specimens Int_90 also showed significant improvement over the non-fiber specimen, its ductility at peak load was 2.8 times its ductility at 1.5% drift. Initial yielding of the slab reinforcement in fiber reinforced interior connections occurred earlier in the test routine than the plain concrete specimen, implying more effective participation of the slab.

Among the exterior connections, the specimen Ext_60 had the highest ductility of about three times the ductility of the plain concrete specimen. The specimens Ext_90 and Ext_30 had ductilities about 2.5 times that showed by Ext_0. These results suggest that the use of fiber reinforcement was effective in enhancing the ductility of exterior connections, and that better response could be obtained by keeping the fiber content about 60 kg/m^3.

2.6 *Overall connection response*

Fiber reinforcement increases the tensile strength of the concrete matrix and it prevents its early disintegration under load reversals thus improving the overall response of both interior and exterior slab-column connections. The most important effect of the enhanced properties of the fiber reinforced concrete on the performance of interior connections was the increase in both the connection shear strength and the drift capacity. Interior connections with a higher fiber content failed in flexural mode rather than in punching shear, and also reached a larger drift and load before failure.

In exterior connections, the presence of fibers appears to promote a better distribution of stresses across the slab width, and helps maintain the integrity of concrete. Since none of the exterior connections failed in punching, the influence of fiber presence on the mode of failure could not be determined. However, the presence of fiber helped reduce the degradation of stiffness in exterior connections and also the loss of strength after the peak load was smaller compared with the non-fiber exterior connection. The most significant effect of fiber reinforcement in exterior connections was the improved ductility of the connections.

3 CONCLUSIONS

The following conclusions may be drawn based on the comparison of observed response between fiber reinforced and non-fiber slab-column connections.

1. Adding fiber reinforcement to slab-column connections improved their seismic response. However, the enhancements were more substantial in interior connections than in exterior connections.
2. Increasing the amount of reinforcement in interior connections changed the failure mode from punching shear to flexural yielding of the slab.
3. Fiber reinforcement improved the ductility of both interior and exterior connections and reduced the degradation of lateral stiffness.
4. The optimum amount of fiber reinforcement for an overall improved seismic behavior of connections was observed to be between 30 and 60 kg/m^3 of concrete.

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