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BEHAVIOUR OF BEAM-COLUMN JOINTS CAST USING SELF-CONSOLIDATING CONCRETE UNDER REVERSED CYCLIC LOADING

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SUMMARY

Multi-storey reinforced concrete structural frames are among the most congested structural elements. Placing and consolidating concrete in such structural frames imposes substantial technical challenges. This offers a unique area of application for self-consolidating concrete because of its inherent ability to flow under its own weight and fill congested sections, complicated formwork and hard to reach areas. However, research is needed to demonstrate the ability of SCC structural frames to adequately resist vertical and lateral loads. In the present study, full-scale 3-m high beam-column joints reinforced as per the Canadian Standard CSA A23.3-94 [1] and ACI-352R-02 [2] were made with ordinary concrete and self-consolidating concrete. They were tested under reversed cyclic loading applied at the beam tip and at a constant axial load applied on the column. The beam-column joint specimens were instrumented with linear variable displacement transducers and strain gauges to determine load-displacement traces, cumulative dissipated energy and secant stiffness. This paper compares the performance of reinforced normal concrete and self-consolidating concrete structural frames and discusses the potential use of SCC in such structural elements.

INTRODUCTION

Self-consolidating concrete (SCC) is a relatively recent development in concrete technology; it was first introduced in Japan in the late 1980's [3]. However, it has been predicted that within the next decade, SCC would replace a large portion of normal concrete [4, 5], especially in developed countries. SCC has been generating significant interest and its usage is gaining momentum in various projects worldwide. It is a highly flowable yet stable concrete that can easily flow and consolidate, even in congested sections or complicated formwork, with little or no vibration and without undergoing considerable segregation or bleeding. SCC is usually produced using available conventional concrete materials. Its mixture proportions are based on creating high flowability while preserving a low water/cementitious materials ratio. This can be achieved through the use of high-range water reducing admixtures (HRWR) often in conjunction with rheology-modifying admixtures to ensure the stability and homogeneity of the mixture. The advantages of SCC over conventionally vibrated normal concrete (NC) include reducing noise on

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construction sites and faster placement, thus increasing pour heights. Moreover, SCC insures improved finish, hence reducing surface remedial costs and minimising wear and tear on formwork.

A substantial portion of the research performed on SCC was dedicated to its rheological and hardened properties. Nagai *et al.* [6] studied the use of superworkable concrete in thin walled prestressed precast concrete members. Their study showed an exceptional capacity of SCC to fill voids in heavily reinforced sections as thin as 60 mm with no significant segregation and no deleterious effects on durability. Research was also conducted on the compatibility of SCC with NC in sandwiched construction as a mean to reduce cost [7]. It was found that when casting SCC in congested areas and NC elsewhere in a sandwiched manner, members behave satisfactorily.

Limited studies investigated the structural performance of SCC in congested members compared to that of normal concrete (NC) [8, 9] and no study dedicated to the seismic performance of SCC was accessible in the open literature. Persson [10] performed a comparative study on NC and SCC to conclude that for similar concrete strength, both concrete types behave similarly in terms of modulus of elasticity, creep and shrinkage. However, the relatively lower coarse aggregate content in SCC may result in lower contribution to the shear resistance produced by aggregate interlock. The study performed by Schiessl and Zilch [11] confirmed such behaviour through a monotonic test. Using roughness measurements, they found that crack surfaces of SCC were smoother than those of NC and that at a similar normal stress across the crack, SCC specimens exhibited lower shear stress resistance. This behaviour could be a concern, especially in the case of seismic loading.

For instance, moment-resisting frames (MRF's) usually contain congested areas of reinforcement. Such frames would be among the applications most benefiting from SCC. Nevertheless, the nature of reversed loading of MRF's in the event of an earthquake and the resulting plastic hinging would impose cautiousness when SCC is used in such applications. Although, SCC has been used in several buildings such as the Millennium Point Building in Birmingham, New Zealand [4] without reported problems, investigations on the behaviour of SCC under cyclic loading are needed for a wide implementation of this material in earthquake-resistant structures.

Several recent earthquakes demonstrated that beam-column joints are vital elements in keeping structural integrity. Joints failures and other types of non-ductile failures were a major focus of the testimony of Thomas D. O'Rourke [12] to the U.S. House of Representatives Committee on Science regarding lessons to be learned from earthquake events in major cities.

In this paper, the behaviour of SCC beam-column joints under reversed cyclic loading is investigated and compared to that of NC beam-column joints, and the use of SCC in structural frames is discussed.

EXPERIMENTAL PROGRAM

Beam-column joints can be isolated from plane frames at the points of contraflexure. The beam of the current test unit is taken to the mid-span of the bay, while the column is taken from the mid-height of one storey to the mid-height of the next storey. Two standard beam-column joints (*J1* and *J3*) were designed as per the current CSA A23.3-94 [1] requirements with sufficient shear reinforcement in the joint area and in the hinging areas of the column and beam. The column is 3000 mm high with cross-section dimensions of 250x400 mm. The beam's length is 1750 mm from the face of the column to its free end with a cross-section of 250x400 mm. The longitudinal reinforcement used in the column is 14 M15 bars (M15 is equivalent to a 16.0 mm diameter bar) without splicing. The transverse reinforcement in the column was two M10 closed rectangular ties. The ties are spaced at 80 mm inside the joint and along 500 mm above and below it (one sixth of the floor's height) then spaced at 125 mm for the rest of the floor height. The top and bottom longitudinal reinforcements of the beam are 6 M15 bars each. The transverse reinforcement of the beam is M10 rectangular ties starting at 50 mm from the face of the column. The ties are spaced at 80 mm for the 800 mm adjacent to the column (equivalent to twice the beam depth) and then spaced at 120 mm for the remaining 840 mm, ending at 60 mm from the free end of the beam. The longitudinal rebar size and transverse reinforcement for the joint and hinging zones confinement are code conforming. Reinforcement details for the tested specimens are shown in Figure 1. NC and SCC were used to cast specimens *J1* and *J3*, respectively. Concrete mixture proportions for both specimens are shown in Table 1. No vibration was used for casting the SCC specimen. Upon the release of the formwork, it was clear that the specimen constructed with SCC had less surface irregularities in comparison with the one made with NC in which the steel reinforcement was exposed at various locations despite the use of vibration.

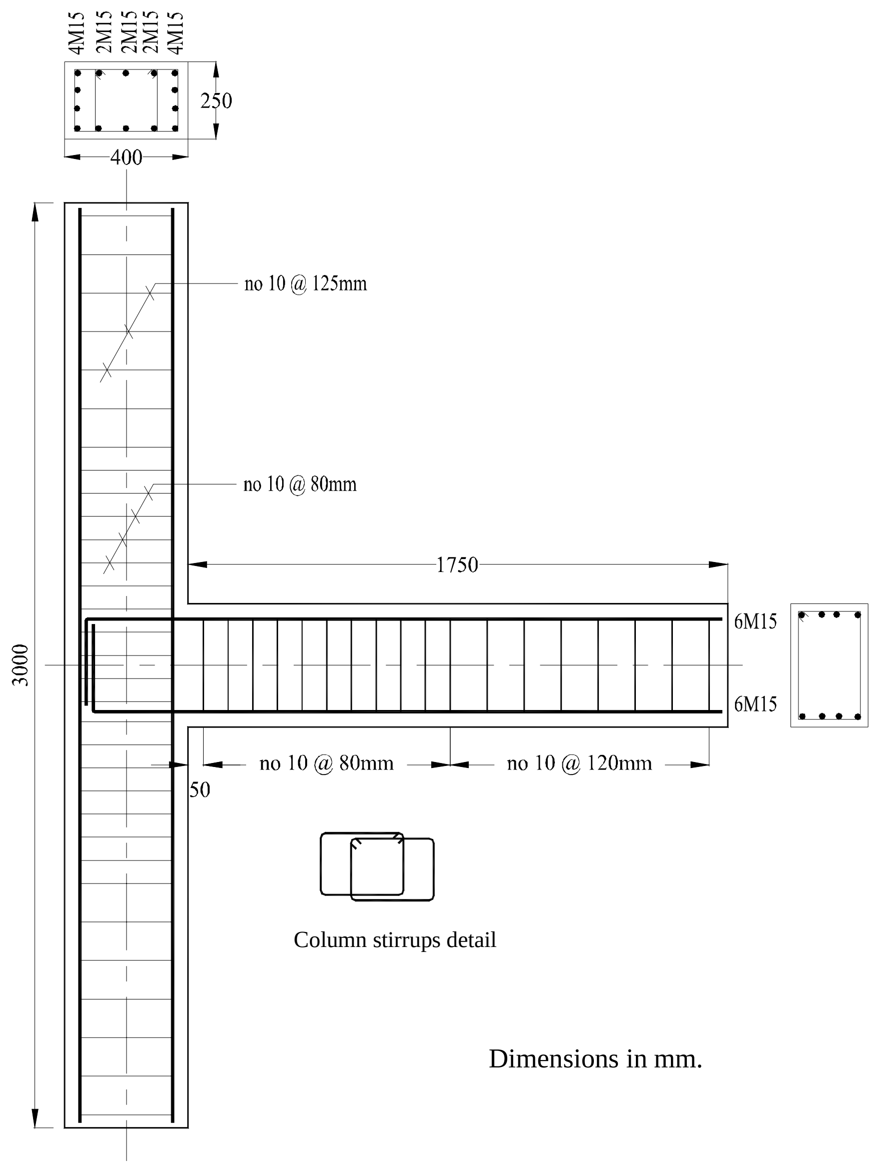

Figure 1. Reinforcement details for the specimens.

Table 1. Concrete mixture proportions for the tested specimens.

	NC - J1	SCC - J3
Cement (kg/m^3)	330	400
Sand (kg/m^3)	790	850
Gravel (kg/m^3)	1130	850
W/C	0.34	0.40
HRWR (L/m^3)	---	4.0
WRA (mL/m^3)	6.6	---
VEA (g/m^3)	---	120
7 d f_c' (MPa)	37.2	33.3
28 d f_c' (MPa)	50.9	50.4
Slump (mm)	50	---
Slump flow (mm)	---	530

Test Setup and Procedure

The beam-column joint specimens were tested under reversed cyclic loading applied at the beam tip. The selected loading pattern is intended to cause forces that simulate high levels of inelastic deformations that may be experienced by the frame during a severe earthquake. The selected load history consisted of two phases. The first phase was load-controlled followed by a displacement-controlled loading phase.

In the first phase of loading, two load cycles at approximately 10% of the estimated strength of the specimen were applied to check the test setup and ensure that all data acquisition channels were functioning properly. This was followed by two load cycles reaching the concrete cracking load in the beam. These in turn were followed by two cycles at the load causing initial yield of the bottom longitudinal steel bars in the beam. The displacement at initial yield of the steel, δ_y, was recorded and used in the subsequent displacement-controlled phase of loading.

The second phase of loading after first steel yield was displacement-controlled and consisted of applying incremental multiples of the yield displacement, δ_y (previously recorded at initial yield). Two load cycles were applied at each ductility level to verify the stability of the specimen. The ductility level is expressed in terms of a ductility factor, μ, which is defined as the ratio of the beam tip displacement, δ, to the displacement at first yield of the principal steel reinforcement, δ_y. The cyclic loading sequence is shown in Figure 2. The test was stopped when the load carrying capacity of the subassemblage dropped to about 50% of its maximum value.

The specimens were placed in the test rig to mimic a hinge support at the base of the column and a roller support at the top part of the column. The roller support was created using a 2 cm vertical slot which allowed vertical deformation in the column as well as the transmission of the column's axial load from the hydraulic jack to the lower hinge support. The cyclic load was applied at the beam tip using a loading ram through a greased pin connection at an arm length of 1670 mm measured from the column face. A schematic of the test setup is shown in Figure 3.

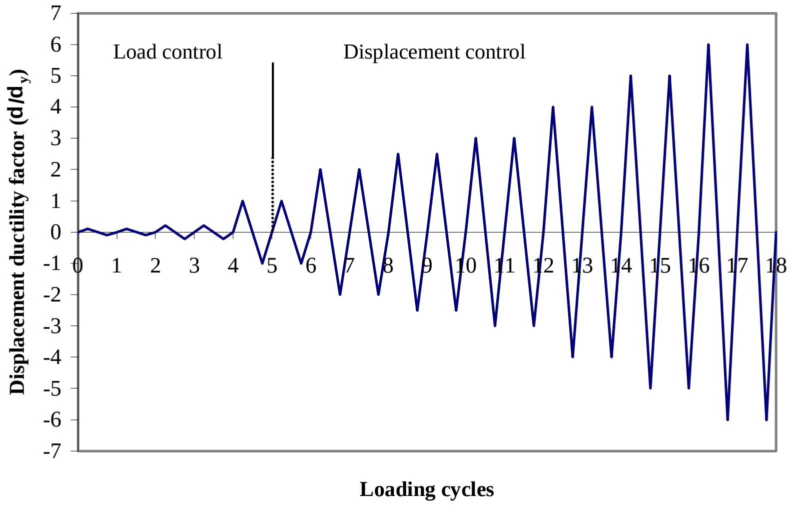

Figure 2. Load history for the reversed cyclic load test used in this study.

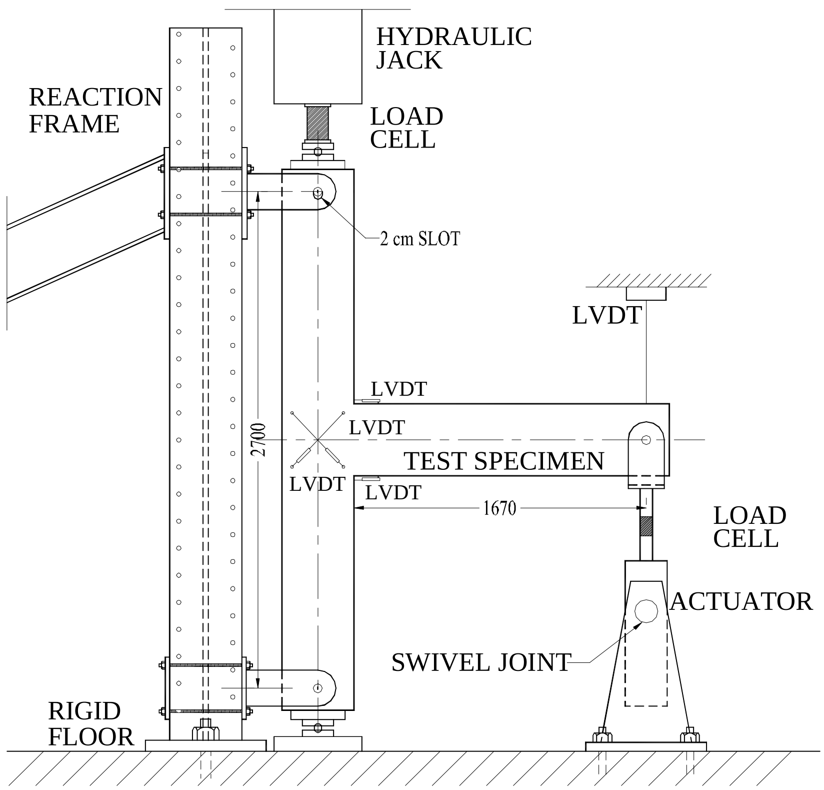

Figure 3. Test setup.

RESULTS AND DISCUSSION

Behaviour of Specimens

The load displacement plots for the NC (*J1*) and SCC (*J3*) specimens are shown in Figures 4 and 5, respectively. For the NC specimen, the yield of the beam's longitudinal steel was reached at an average beam tip load of 107 kN and the corresponding average yield displacement was 28 mm (based on push up and pull down values), whereas for the SCC specimen, the yield load was 104 kN at a displacement of 27 mm.

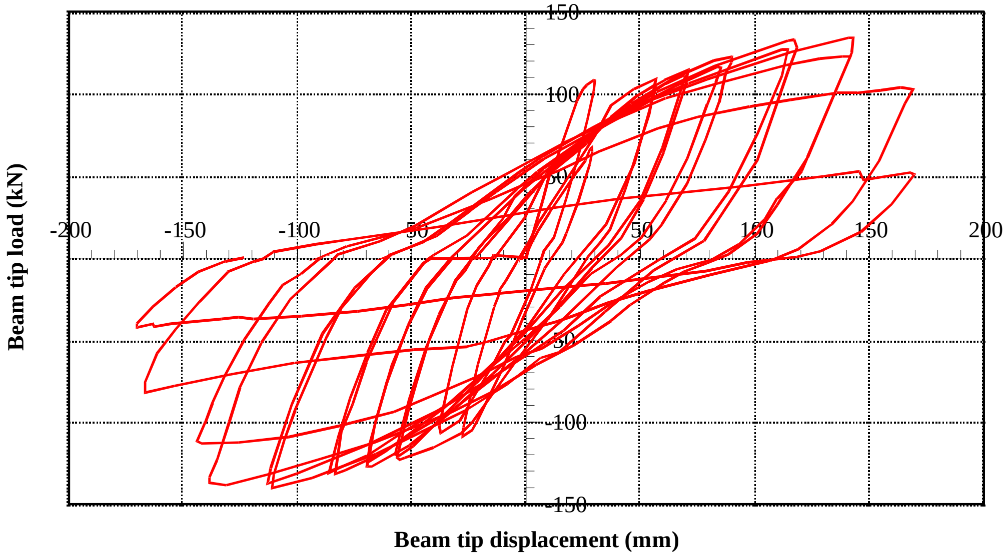

Figure 4. Load displacement relationship for NC specimen *J1*.

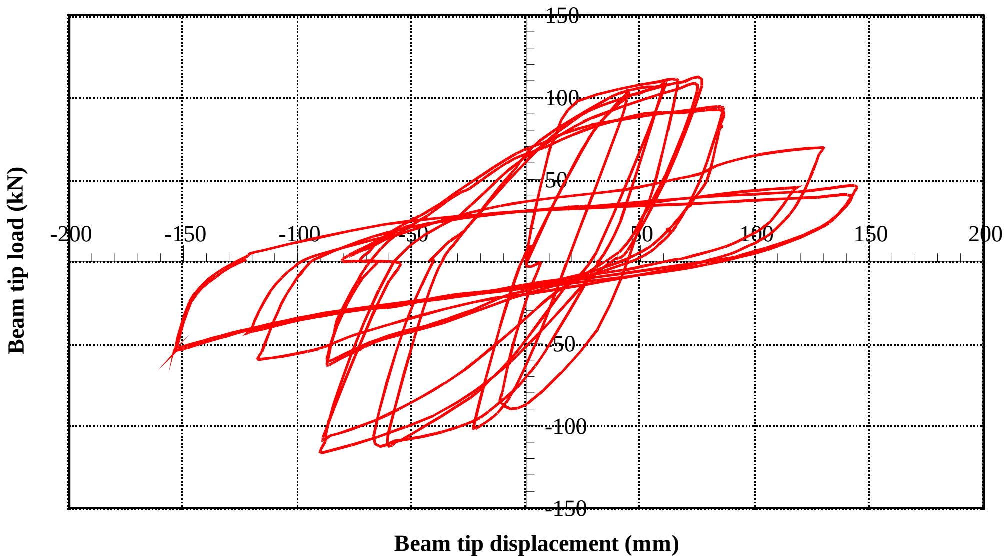

Figure 5. Load displacement relationship for SCC specimen *J3*.

The onset of diagonal cracks in the joint area took place at a beam tip load of 60 kN and 65 kN for specimens *J1* and *J3*, respectively. Additional cracks appeared thereafter as loading progressed at a uniform spacing, but remained within a very fine width throughout the test. At a ductility factor of 2, the beam became extensively cracked along a distance equal to its depth from the face of the column for both specimens. At a ductility factor of 3, the SCC specimen started exhibiting lower load carrying capacity and this became clearer in subsequent load cycles. For both specimens the column's axial load was maintained and the joint areas were still intact, except the presence of fine diagonal cracks. The faster decline of the load carrying capacity of the SCC specimen could be attributed to the fact that its lower coarse aggregate reduced the contribution of friction due to aggregate interlock to the total shear resistance mechanisms, especially at high levels of displacement. Final crack patterns for the NC (*J1*) and the SCC (*J3*) beam-column joint specimens are shown in Figure 6 (a) and (b), respectively.

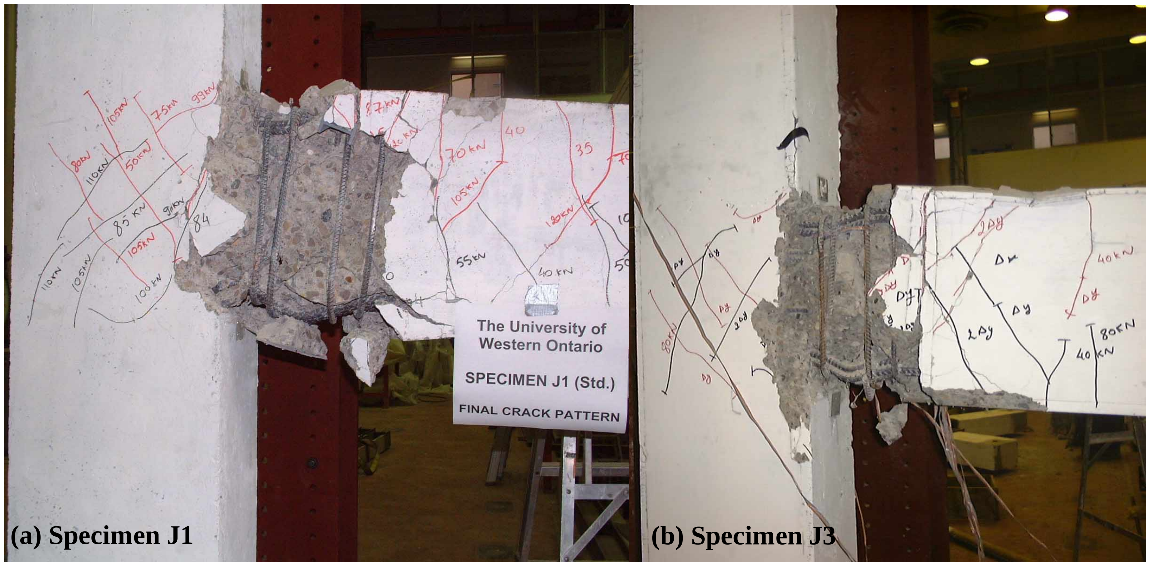

Figure 6. Final crack pattern for (a) NC specimen (*J1*), and (b) SCC specimen (*J4*).

Load - Displacement Envelope Relationship

For each of the beam-column joint specimens, the envelope of the beam tip load-displacement relationship is plotted in Figure 7. The SCC specimen (*J3*) had a comparable capacity to that of the normal concrete specimen (*J1*) up to a displacement level of about 75 mm (corresponding to a 4.5% drift), which could be considered as structurally adequate. Subsequently, the reserve strength of the SCC specimen was lower and a plastic hinge formed in the beam. The maximum displacement ductility achieved by the NC specimen was 6 compared to 5 for the SCC specimen. It is worth mentioning that for both specimens, at the same levels of joint shear input, the calculated joint deformations were comparable. In addition, the beams' plastic hinges formed at equal distances from the column face for both specimens.

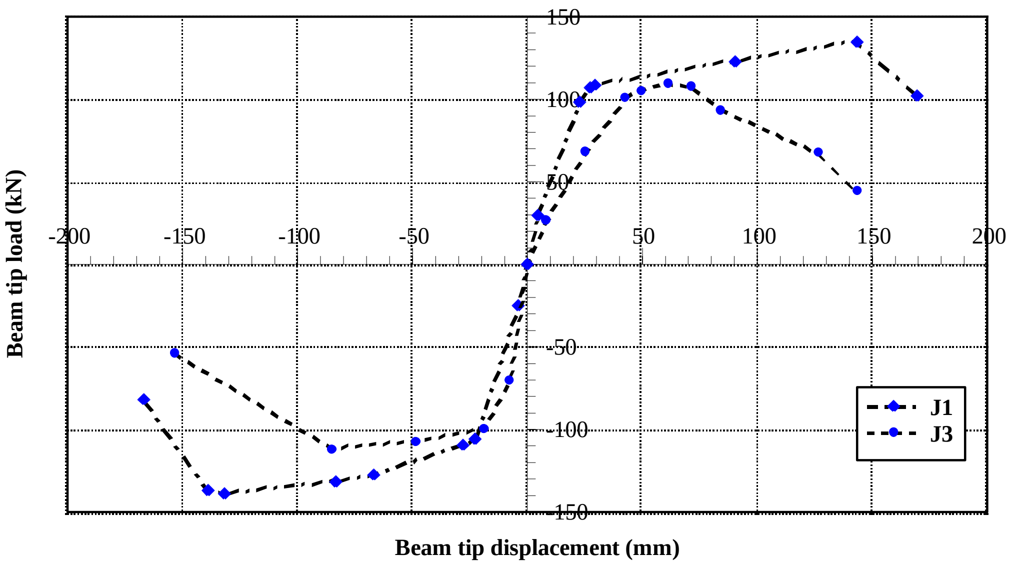

Figure 7. Load-displacement envelopes for the tested specimens.

Cumulative Dissipated Energy

The capability of a structure to survive an earthquake depends on its ability to dissipate the energy input by the ground motion. The cumulative energy dissipated by the beam-column joint specimens during the reversed cyclic load test was calculated by summing up the energy dissipated in consecutive load-displacement loops throughout the test. The energy dissipated in a cycle is calculated as the area that the hysteretic loop encloses in the corresponding beam tip load-displacement plot.

Figure 8 shows a plot of the cumulative energy dissipation versus displacement ductility factor for the NC specimen *(J1)* and the SCC specimen (*J3)*. Results show that the SCC joint had higher energy dissipation till a ductility level of 3. Afterwards, the NC joint specimen showed higher energy dissipation capacity with an overall 38% superiority.

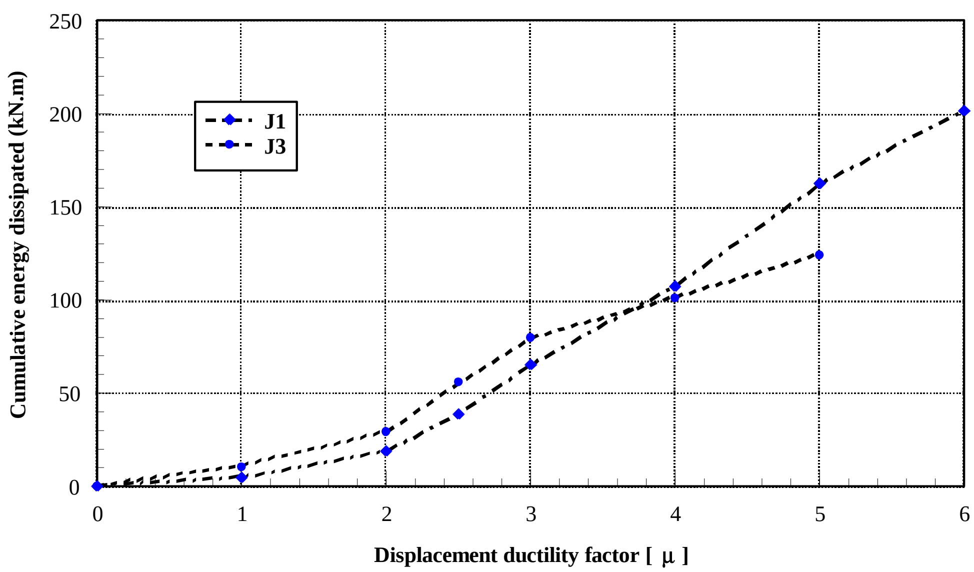

Figure 8. Cumulative energy dissipated for the tested specimens.

Secant Stiffness

Secant stiffness is evaluated as the peak-to-peak stiffness of the beam tip load-displacement relationship. It is calculated as the slope of the line joining the peak of positive and negative loads at each given cycle. The secant stiffness is an index of the response of the specimen during a cycle and its strength degradation from one cycle to the following cycle.

Figure 9 shows plots of the secant stiffness for the NC and SCC beam-column joint specimens versus the storey drift. The storey drift is calculated as shown in Figure 10 by relating the subassemblage deformation in the test rig to the actual displaced frame case. An examination of the plots indicates that the SCC specimen (*J3*) had higher initial stiffness. After a drift angle of 2%, the NC standard specimen (*J1*) had higher stiffness up to the end of the test. Nonetheless, the SCC specimen (*J3*) exhibited stable strength degradation up to failure. The maximum drift achieved was 9.0% and 7.9% for specimens *J1* and *J3,* respectively.

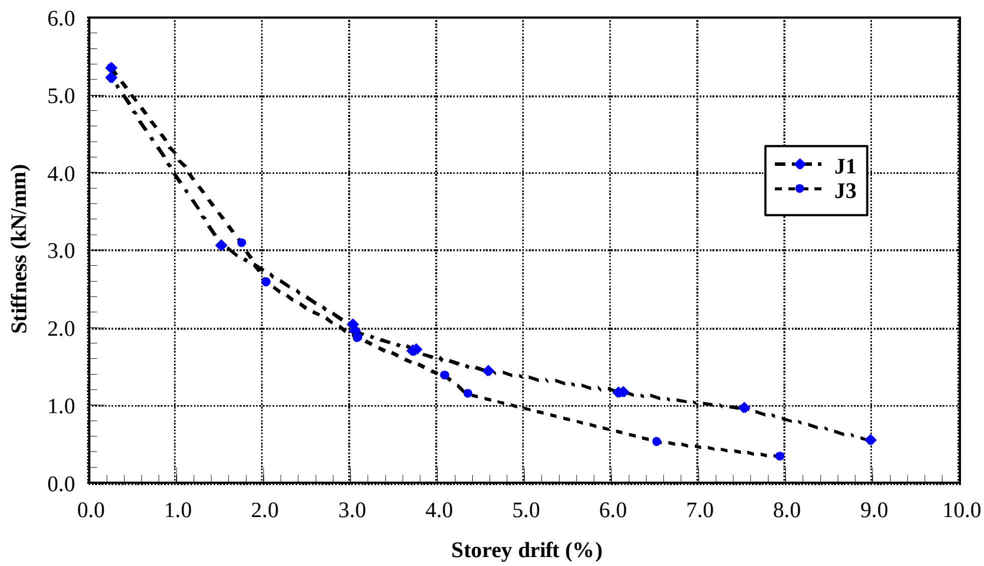

Figure 9. Secant stiffness-displacement ductility factor for the tested specimens.

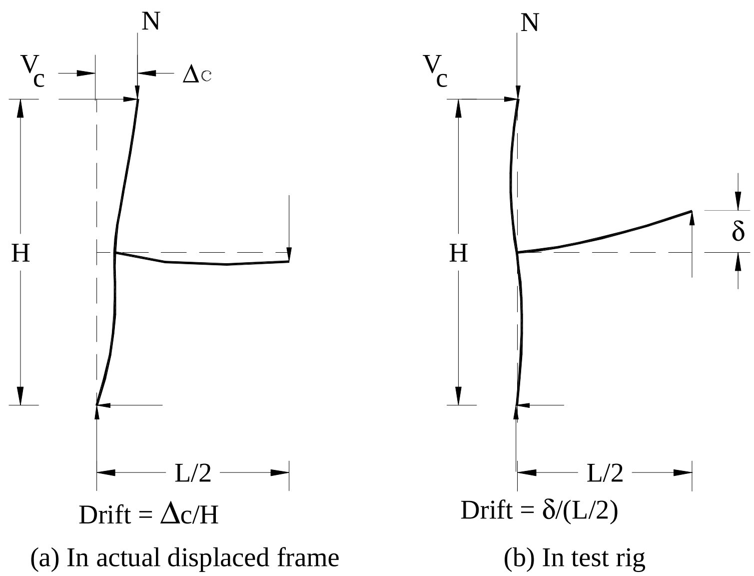

Figure 10. Exterior beam-column subassemblages in (a) displaced frame and (b) test rig.

CONCLUSIONS

Reversed cyclic loading tests were performed on full-scale beam-column joint specimens to compare the performance of normal concrete and self-consolidating concrete in moment resisting frames. Based on experimental observations and analysis of test results, the following conclusions can be drawn:

1. SCC beam-column joints have comparable load capacity to that of NC joints up to a certain ductility level. At high ductility levels, SCC specimens may not maintain the same capacity as NC specimens. While this behaviour could be attributed to the fact that the lower coarse aggregate content in SCC reduced the contribution of the aggregate interlock to the total shear resistance mechanism, further research is required to fully understand this behaviour.
2. The performance of SCC under shear stress in the joint panel was comparable to that of NC in terms of cracking and deformations.

3. The SCC beam-column joint specimen performed adequately in terms of the mode of failure and ductility requirements, assuming that the expected minimum drift requirement is 3%, as recommended in the literature for ductile frame buildings [13].
4. Further studies are needed to investigate the behaviour of SCC under cyclic loading in plastic hinging zones and to quantify aggregate interlock contribution mechanisms for different coarse aggregate contents along with the effect of other mixture design parameters.

REFERENCES

1. CSA A23.3-94, 1994, "Design of Concrete Structures", Canadian Standards Association, Rexdale, Ontario, Canada, 209 p.
2. ACI 352R-02, 2002, "Recommendations for Design of Beam Column Connections in Monolithic Reinforced Concrete Structures", Joint ACI-ASCE Committee 352, Technical Committee Document 352R-02, 37 p.
3. Nagamoto, N. and Ozawa, K., 1997, "Mixture Properties of Self-Compacting, High-Performance Concrete", Proceedings of the Third CANMET/ACI International Conference on Design and Materials and Recent Advances in Concrete Technology, ACI SP 172, Kuala Lumpur, Malaysia, pp. 627-637.
4. Henderson, N., 2000, "Self compacting concrete at Millennium Point", Concrete for the Construction Industry, The Concrete Society, UK, April 2000, pp. 26-27.
5. Campion, M. J., and Jost, P., 2000, "Self Compacting Concrete- Expanding the Possibilities of Concrete Design and Placement", Concrete International, Vol. 22, No. 4, pp. 31-34.
6. Nagai, T., Kojima, T., and Miura, T., 1999, "Application of High Strength/Superworkable Concrete to Thin-Wall Prestressed Concrete Products", Magazine of Concrete Research, Vol. 51, No. 3, pp. 153-162.
7. Ho, D. W. S., Sheinn, A. M. M. and Tam, C. T., 2001, "The Sandwich Concept of Construction with SCC", Cement and Concrete Research, Vol. 31, No. 9. pp. 1377–1381.
8. Sonebi, M., Bartos, P., and Tamimi, A., 2001, "Flexural Response of Reinforced Beams Cast with Self-Compacting Concrete", Proceedings of the Second International Symposium on Self-Compacting Concrete, Tokyo, Japan, RILEM Publications S.A.R.L., pp. 517-526.
9. Khayat, K. H., Paultre, P., and Tremblay S., 2001, "Structural Performance and in-Place Properties of Self-Consolidating Concrete Used for Casting Highly Reinforced Columns", ACI Materials Journal, Vol. 98, No. 5, pp. 371-378.
10. Persson B., 2001, "A Comparison Between Mechanical Properties of Self-Compacting Concrete and the Corresponding Properties of Normal Concrete", Cement and Concrete Research, Vol. 31, No. 2, pp. 193-198.
11. Schiessl, A. and Zilch, K., 2001, "The Effect of the Modified Composition of SCC on Shear and Bond Behaviour", Proceedings of the Second International Symposium on Self-Compacting Concrete, Tokyo, Japan, RILEM Publications S.A.R.L., pp. 501-506.
12. O'Rourke, T. D., 1999, "The Turkey, Taiwan, and Mexico City Earthquakes: Lessons Learned", Hearing of the Subcommittee on Basic Research U.S. House of Representatives Committee on Science, October 20, 1999. Web address *http://www.eeri.org/Features/ORourke99/HTML/index.htm*
13. Corley, W. G., 1995, "Ductility of Columns, Walls, and Beams-How Much is Enough?", American Concrete Institute, Proceedings of the Thomas Paulay Symposium on Recent Developments in Lateral Force Transfer in Buildings, SP-157, La Jolla, California, pp. 331-350