CRITICAL CRACK WIDTH IN LARGE FLEXURAL MASONRY BEAMS UNDER SERVICE LOAD

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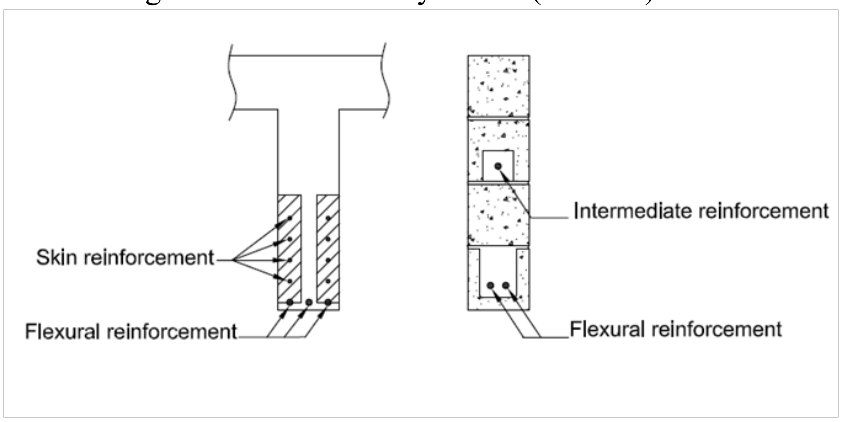
ABSTRACT
Concrete masonry components crack when they are subjected to flexural loading and these cracks can lead to serviceability problems. Large masonry flexural beams are those with a height of 600 mm or larger. Currently, it is anticipated that these cracks in large masonry flexural beams can extend upward and create a larger crack width in the zone which lies in between the primary flexural reinforcement and the neutral axis. This zone is referred to as the intermediate zone. Accordingly, current Canadian masonry design standard, CSA S304.1, recommends using one No. 15 bar at a spacing of 400 mm as intermediate reinforcement in beams up to 240 mm wide to minimize the intermediate crack width. However, it is presumed that this recommendation is not based on any test data since no studies on large masonry beams were found in the public domain. Hence, this study was undertaken to verify the current provision of CSA S304.1 about the requirement of intermediate reinforcement in large masonry beams. The study was completed using laboratory-based experimental method. It was found that the current provision of the Canadian standard needs revision. This paper discusses test specimens, test procedure, and test results obtained from this study.

KEYWORDS: large masonry beam, intermediate reinforcement, intermediate crack width, serviceability limit states

INTRODUCTION
Masonry beams that are 600 mm or higher are known as large reinforced masonry beams (LRMB) (CSA 2004a). Such large masonry beams are used in openings for industrial doors and when a large span is required. The spans of these beams are large and hence, the depth required for such span could easily be more than 600 mm. Unlike deep beams, these beams are designed as flexural beam and they are expected to fail in flexure. Behaviour of large reinforced concrete beam (LRCB) has been studied extensively. Hence, it is now well accepted that the LRCB develops side-face cracks which are the cracks that form in between the flexural reinforcement and the neutral axis. It was found that the width of such cracks can be larger than the primary flexural cracks, those form at the extreme tension face (Frosch 2002; Frosch 1999; Frantz and Breen 1980; Broms 1965; Broms 1964; Kaar and Mattock 1963). The side-face cracks in LRCB can cause serviceability and strength problems. Previous researches showed that skin reinforcement which is evenly distributed smaller diameter rebars provided close to the face of the web of the LRCB is effective in limiting the width of side-face cracks to the acceptable serviceability limits (Figure 1a). Consequently, many design standards and codes have incorporated the provision of skin reinforcement in LRCB (ACI 2008; CSA 2006; CSA 2004b; AASHTO 2002).

It is presumed that the LRMB would also develop similar cracks in between the neutral axis and the primary reinforcement. Such cracks in LRMB are called intermediate cracks instead of side-face cracks, though it is not known why a different name for such cracks is used in masonry construction. Clause 11.2.6.3 of Canadian standard, CSA S304.1 (2004a) recommends using one No. 15 rebar with 400 mm spacing along the height of the LRMB when the beam width is up to 240 mm. The intention of this clause is to limit the width of intermediate cracks to the acceptable serviceability limits. This reinforcement is called intermediate reinforcement in the Canadian standard (CSA 2004a) as shown in Figure 1(b). Literature review revealed that no previous research on LRMB was undertaken to study the crack pattern and the crack width in LRMB. Hence, it is presumed that the recommendation on intermediate reinforcement in the Canadian standard is purely intuitive and probably based on the studies completed on LRCB. Hence, the current study was undertaken to understand the behaviour of LRMB and its crack patterns and crack growth primarily under service load. The research was completed using full-scale experimental tests on large reinforced masonry beams (LRMBs).



(a): Skin reinforcement (b): Intermediate reinforcement

Figure 1: Skin and intermediate reinforcement

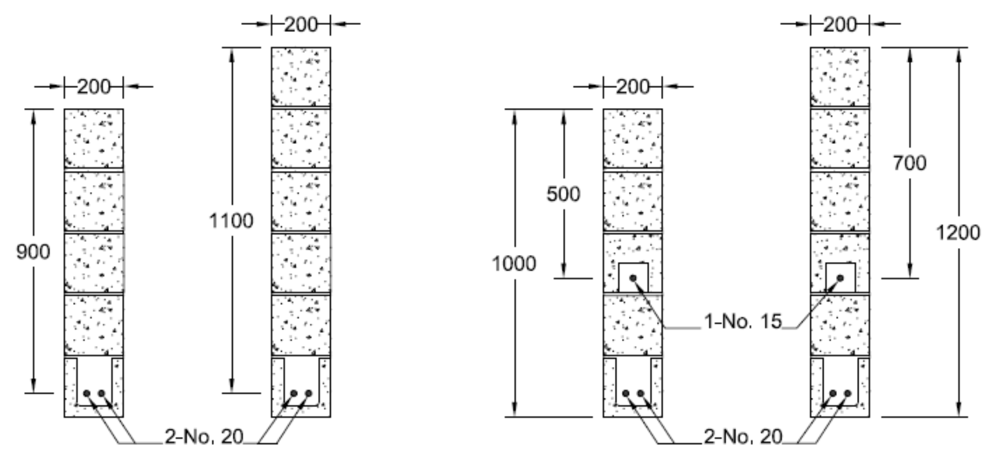
TEST SPECIMENS AND TEST METHOD

The test matrix is shown in Table 1. A total of four full-scale masonry beams were built and tested in the structural engineering lab at the University of Windsor. Standard stretcher and lintel block units were used to build these beams. The nominal dimensions of these blocks were 400 mm x 200 mm x 200 mm (CSA 2004c). The lintel block units were used in the bottom course to be able to place the flexural reinforcement. All beams were 200 mm wide. Two No. 20 steel rebars were used as the primary flexural reinforcement and single-legged stirrups made of No. 10 at 400 mm on centres were provided in the shear span to prevent formation of any shear cracks even under service load conditions.

These beams with two different heights were built and they were 1000 mm and 1200 mm high. Hence, as per the definition of Canadian standard, these beams were large masonry beams (LRMBs). Total lengths of these beams were 9 m and 10 m, respectively. Hence, these beams are separated into two groups: group 1 and group 2 for 9 m long and 10 m long beams, respectively. Clear span between the two supports of these two beams were 8.6 m and 9.6 m, respectively. Each group had two beams: one with intermediate reinforcement and the second one without intermediate reinforcement as recommended in CSA S304.1 (2004a) to verify the effect of intermediate reinforcement on the width of intermediate cracks in LRMB. One No. 15 bar was provided as the intermediate reinforcement as shown in Figure 2. All the beams were fully grouted with fine grout (CSA 2004d). In Table 1, Beam B100N means the height of the beam was 100 cm or 1000 mm and it had no intermediate reinforcement. On the other hand, Beam B120Y was 120 cm or 1200 mm high and it had one No. 15 rebar as intermediate reinforcement which was placed at 500 mm above the bottom face of the beam.

Table 1: Specimen matrix and test specimen details

ID	Group	L (mm)	h (mm)	d (mm)	Moment span (mm)	Shear span (mm)
B100N	1	8600	1000	900	1000	3700
B100Y						
B120N	2	9600	1200	1100	1000	4300
B120Y						



(a): Without intermediate rebar (b): With intermediate rebar

Figure 2: Cross sectional view of beam specimens

All the beams were loaded using the monotonically increasing displacement control method and a four-point bending load was simulated to facilitate a constant bending region at the mid span as shown in Figure 3. The length of constant moment region was 1000 mm. Pin-roller boundary conditions were simulated to make these beams simply supported. The load, P was increased slowly using the displacement control method and the loading was held unchanged several times to monitor and record the crack width data and crack growth pattern.

Various test data was acquired from these beam tests and these are: load, displacement, strain, and crack width using a computerized data acquisition system. Load data from the loading actuator was obtained through a loadcell and the information on the displacement applied was acquired from the linear variable displacement transducers (LVDT) mounted on the loading actuator. Several other displacement gauges were installed on the vertical surface along the height of the beam and the gauge length for these displacement gauges was 600 mm (Figure 4). These data obtained from the displacement gauges were later used to determine the strains along the height of the beam and its neutral axis. Strain gauges were installed on the flexural rebars at the mid-span of the beam to acquire strain data from these steel rebars. The strain gauge strain data was later used to determine the service and yield loads. A high-resolution digital camera was used for obtaining the crack width data along the height of the beam as the load increased. These cracks were measured at pre-decided locations in the constant moment region as shown by the grid lines in Figure 5.

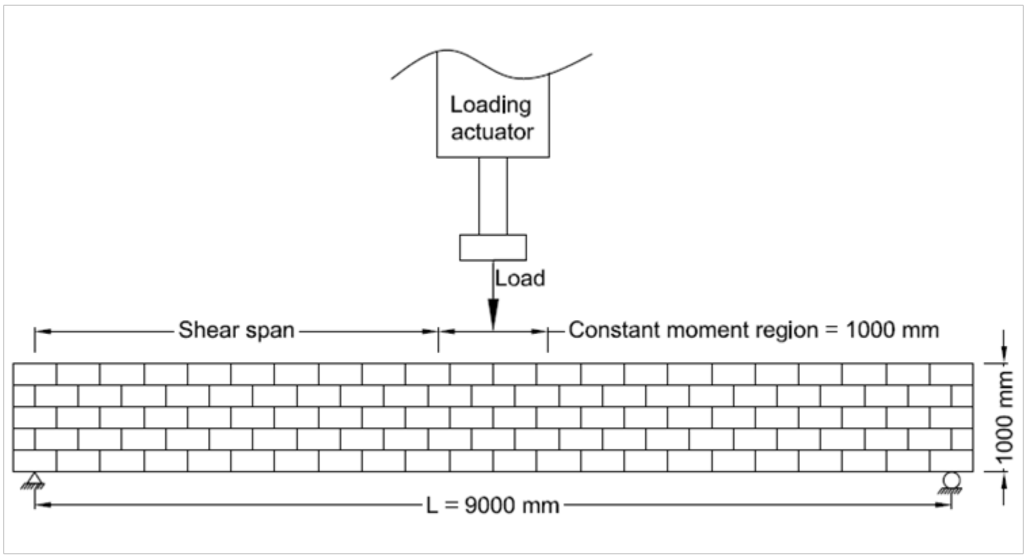


Figure 3: Schematic of test setup

TEST RESULTS AND DISCUSSION

Material tests were conducted before constructing the beam specimens in accordance with Canadian standards (CSA 2004c; CSA 2004d). The specified strength of block units was 20.1 MPa and the average strength of mortar and grout were found to be 23 MPa and 28 MPa, respectively. Four-course high prism specimens were built and tested to determine the specified compressive strength of masonry. The specified compressive strength of hollow and grouted masonry was found to be 22.1 MPa and 11.4 MPa, respectively. The yield strength and modulus of elasticity of steel rebar used in these beams were found to be 498 MPa and 205 GPa, respectively

The load-deformation behaviours of beams from both groups are shown in Figure 6. The objective of this research was to study the crack patterns and crack width under service load of LRMBs with and without intermediate reinforcement. The service load was determined as the load that produced 1200 microstrain in the primary flexural rebars. Yield strain for these rebars was determined to be 2100 microstrain. This figure shows that cracks in these beams began at about 20 kN load and yielding occurs at a load value of 110 kN to 135 kN. The load-deformation behaviour in between the cracking load and yielding load was almost linear. However, the stiffness of the beams in this region was lower than the pre-cracking stiffness and much higher than post-yielding stiffness which is expected. The maximum load applied at the time when test was terminated reached approximately 120 kN to 140 kN. The tests were terminated at this stage to avoid any damage to the loading frame, loadcell, and other equipment. As it was desired, no shear cracks were found, not only at the service load level but also at the higher load when the test was terminated.

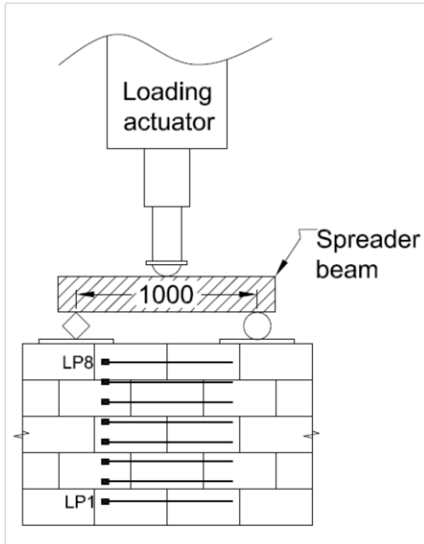


Figure 4: Linear potentiometer locations

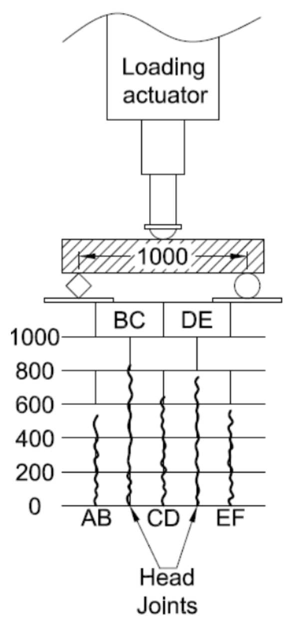


Figure 5: Cracks for beam specimens

The depth of the neutral axis was determined from the displacement data obtained from the displacement gauges mounted on the vertical face of the beam and strain gauges mounted on the primary flexural rebars. The location of the neutral axis was required for the determination of the tension zone depth of the beam. The tension zone depth at the yield load was determined to be 780 mm and 960 mm for beams from groups 1 and 2, respectively. The tension zone depth was large since these beams were designed to be highly under-reinforced. High tension zone depth was preferred to create wider intermediate cracks and thus, to simulate the worst scenario for the LRMB when the intermediate crack width is a matter of concern.

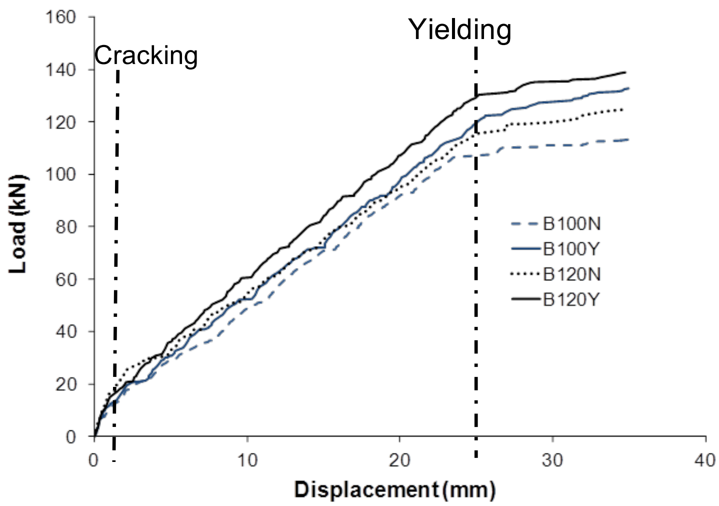


Figure 6: Load-deformation behaviour of beam specimens

The first crack in all the beams initiated at one of the head joints at the bottom course of the constant moment region (Figure 5). However, more cracks formed at the other head joints in the constant moment region and also in between two head joints splitting the lintel block units as the applied load increased. These cracks then grew in length along the height of the beam at almost right angle with the beam's longitudinal axis as load and displacement values increased further. However, the growth of cracks in beams with and without intermediate reinforcement was slightly different. It was found that the beams without intermediate reinforcement, the cracks grew in length until a higher value of strain (about 1000 microstrain) in the primary flexural rebars whereas, for beams without the intermediate reinforcement, the crack stopped growing in length at a much lower flexural steel strain (about 600 microstrain). As a result, the cracks in beams without intermediate reinforcement began to grow wider at a much lower strain (600 microstrain) than the beams with intermediate reinforcement (1000 micro strain). It is believed that this resulted in much wider intermediate cracks in beams without intermediate reinforcement.

Figure 7 shows the crack width along the height of the beams in group 2 (Table 1). This figure shows that the intermediate reinforcement has beneficial effect in reducing the crack width over its entire length. However, the intermediate reinforcement, which was provided at 500 mm above the bottom face of the beam in accordance with the Clause 11.2.6.3 of Canadian standard (CSA 2004a), did not show any significant reduction in crack width at the level of intermediate rebar.

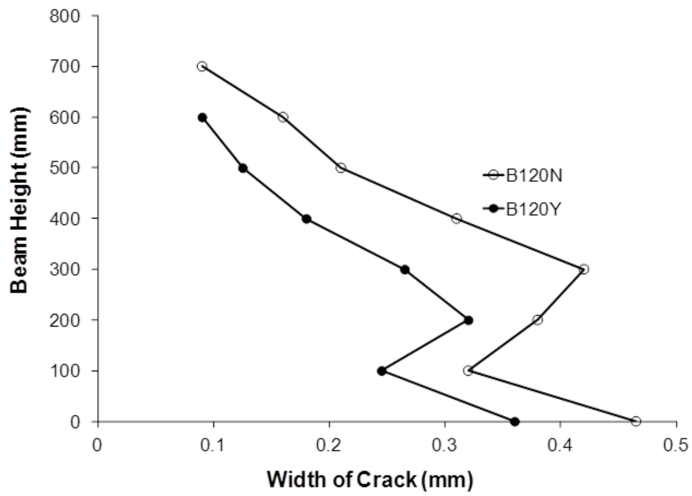


Figure 7: Crack width profile for beams of group 2

Figure 8 shows a similar plot for strain distribution along the height of the beams but for specimens in group 1. It can be observed that the width of the intermediate crack in beam B100N is much smaller than the intermediate crack width for beam B120N in group 2. The height of these beams are 1000 mm and 1200 mm, respectively. Thus, it can be concluded that for large reinforced masonry beams up to 1000 mm high, the width of intermediate cracks under service load is not a matter of concern if the acceptable limit for crack width under service load is considered as 0.40 mm (Gilbert 2009; Frosch 2002; Broms and Lutz 1965). This finding does not endorse the recommendations of the Canadian standard, CSA S304.1 (2004a) which suggests that masonry beams higher than 600 mm require intermediate reinforcement. Hence, this study suggests revising the current height limit of 600 mm for LRMB appears in the current Canadian standard (CSA 2004a) to 1000 mm. This revision suggests removing the excessive conservativeness that currently exists in the standard for the provision of intermediate reinforcement.

It can be observed from Figures 7 and 8 that for the beams without intermediate reinforcement two spikes in crack widths occur along the height of the beam. The first spike is at the extreme tension face (bottom face) of the beam which is expected and obvious. The second spike occurs at about 200 mm to 300 mm away from the extreme tension face. The location of the second spike is much closer to the extreme tension face of the beam if compared with that found by other researchers in large reinforced masonry beams (Gilbert 2009; Frosch 2002; Broms and Lutz 1965). Hence, this study found that the location of critical width of intermediate cracks in LRMB is different from that of LRCB. It is believed that the current provision in the Canadian masonry design standard, CSA S304.1 (2004a) is intuitively adopted based on the test data obtained from LRCBs. Hence, Clause 11.2.6.3 reads that the first intermediate rebar in LRMB is required at 500 mm from the bottom (extreme tension) face of the beam. However, this study found that most effective location of first intermediate rebar is between 200 mm and 300 mm. Hence, this study recommends rewriting this clause to reflect the fact that the first intermediate rebar is required in between 200 mm and 300 mm.

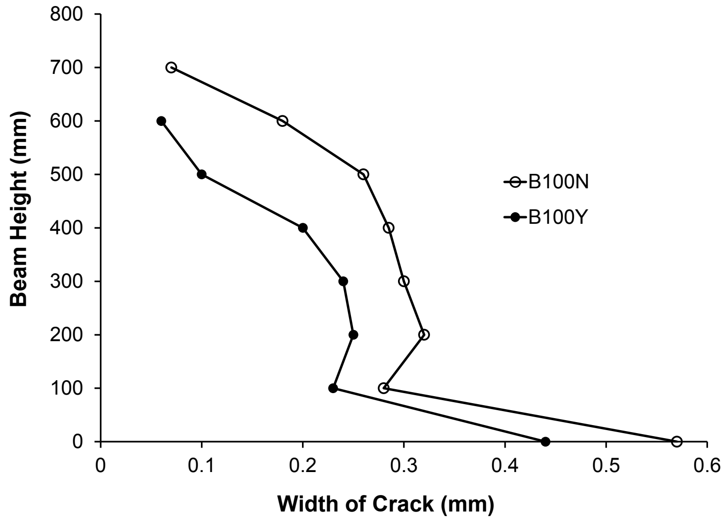


Figure 8: Crack width profile for beams of group 1

CONCLUSIONS

The following conclusions are made based on the test data obtained from the beams tested in this study and hence, the conclusions are limited to these beams.

(1) The beam height limit of 600 mm for a large masonry beam in the current Canadian masonry design standard CSA S304.1 is conservative. This study found that the maximum width of an intermediate crack in 1000 mm high large masonry beam does not pose a serviceability threat. Hence, this study found that this height limit can be increased to 1000 mm.

(2) Current Canadian standard CSA S304.1 recommends using intermediate reinforcement at a vertical spacing of 400 mm. This seems to indicate that the first intermediate rebar is required at 400 mm from the primary flexural rebar which means at about 500 mm from the extreme tension face of the beam. However, this study found that the width of intermediate crack is maximum at about 200 mm and 300 mm from the extreme tension face of the beam. Hence, this study suggests revising the current Canadian provision accordingly.

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