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Strain Rate Effect on Development Length of Steel Reinforcement

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Abstract: Accidental or premeditated explosions have detrimental effects on infrastructure in the vicinity of the centre of explosion and pose major threats to human life. Thus, a lot of research is currently underway to study the effects of explosions on infrastructure systems with an ultimate goal of minimizing infrastructure damage and saving lives. Since reinforced concrete is the most common building material used in blast resistant infrastructure design and construction, understanding the effect of blast loads on reinforced concrete components is vital.

The design philosophy of critical infrastructure systems is energy dissipation through reinforcement yielding (ductility). Thus it is essential to preclude non-ductile failure modes such as shear and bond failures in infrastructure systems. This paper presents an experimental program to investigate the strain rate effects on steel reinforcement-concrete bond. Reinforced concrete beams were tested under static and shock tube testing to investigate the high strain rate effect on development length.

The bond stress was determined to increase with an increased strain rate and that the development length calculated in accordance with CSA A23.3 is adequate to resist the dynamic yield strength of steel reinforcement. The dynamic increase factor for bond stress was determined to be 1.71.

1 Introduction

In recent years, the occurrence of accidental and premeditated explosions has raised concerns about the integrity of critical infrastructures and their ability to protect people from the effects of explosions. The Oklahoma City bombing in 1995 and the September 11, 2001 attacks on the World Trade Centre in New York City have raised concerns about the ability of buildings designed for aesthetic and economy to resist extreme loading from terrorist attacks. Damage from explosive effects is not limited to terrorist action alone. Accidental explosions may have similar detrimental effects on proximate structures. For example, The Halifax explosion that occurred in 1917, from accidental collision involving a cargo ship carrying explosives resulted in many fatalities and collapsed or severely damaged buildings within a 25-km radius from the centre of explosion (MacDonald 2005). There are however, methods available for mitigating some of the damaging effects of explosions and improving the integrity of building infrastructure. These include mitigating window glass hazard and strengthening the exterior façade of buildings to increase their blast resistance.

Reinforced concrete is the most common building material used in blast resistant infrastructure due to its ability to absorb blast energy. The detailing of reinforcing steel in concrete elements is the key to achieving increased structural integrity and ductility. Thus, it is important to attain high-quality bond of reinforcing steel to concrete and to ensure yielding of reinforcement.

While the current level of knowledge on the bond of reinforcing steel to concrete in beams is quite advanced, most of the knowledge is on the effect of static or low-cycle dynamic loading on bond. The effect of dynamic loads, such as impact and blast, on steel reinforcement-concrete bond is a subject of on-going research. Many researchers (Fu et al. 1991, Malvar and Crawford 1998, Le Nard and Baily 2000) have reported changes in steel reinforcement and concrete properties under high strain rates (dynamic loading), but the interaction between the two materials, which is important for bond behaviour, is not well researched.

2 Literature Review

The effect of dynamic loads on reinforced concrete is quite complex. Short duration dynamic loads may affect the properties of concrete and steel in different manners, thus altering the failure modes in reinforced concrete elements from ductile to brittle failure (Yang and Lok 2007). Furthermore, the bond characteristics of concrete to steel reinforcement at high loading rates are not very well researched and may affect the behaviour of reinforced concrete elements.

The blast resistance of a reinforced concrete structure depends on the performance of concrete and steel reinforcement under high strain rates. The load transfer from the steel reinforcement to the adjacent concrete is essential for achieving ductile response. Thus understanding the behaviour of concrete and steel reinforcement in reinforced concrete elements under blast loading is of particular interest. The following sections outline the effect of high strain rate on the properties of concrete and steel reinforcement and the effect on the bond between them.

2.1 Concrete under high strain rates

Many researchers have studied the effect of high strain rates on both the tensile and compressive strength of concrete (Fu et al. 1991, Le Nard and Bailly 2000, Lu and Xu 2004, Yan and Lin 2006) and have reported an increase in strength under high strain rates. Although there are some disagreements in the experimental results regarding the exact magnitude of strength increase between researchers, values of dynamic increase factor (DIF) have been published and recommended for design. The DIF is defined as the ratio of dynamic to static strength. Table 1 provides design DIF values for concrete loaded from close-in and far-range blasts (UFC 2008). The far design range produces pressures that are relatively uniform along the surface of a building, whereas the close-in design range produces relatively short duration non-uniform pressures, leading to localized stresses (UFC 2008).

The dynamic strength of concrete (f'_{dc}) used for design is defined as the product of the dynamic increase factor (DIF) and the static compressive strength of concrete (f'_c) and expressed by Equation 1.

[1] $$f'_{dc} = DIF \times f'_c$$

2.2 Steel Under High Strain Rates

Similarly with concrete, strength characteristics of steel are dependent on the strain rate. Several studies have shown that steel reinforcement undergoing rapid loading experiences an increase in both yield and ultimate strength (Keenan and Feldman 1960, Flathau 1971, Mirza and Macgregor 1979). Furthermore, steels with lower strengths are more sensitive to increases at high strain rates than high strength steels. While many properties of steel change under high strain rates, the modulus of elasticity remains relatively constant. Table 1 presents *DIF* values published in the Unified Facilities Criteria (2008) for yield and ultimate strength of steel reinforcement under both close-in and far design ranges.

Table 1: Dynamic Increase Factors for Concrete and Steel Reinforcement (UFC 2008)

	DIF for Concrete		DIF for Steel Reinforcement			
Type of Stress	*Far Design Range*	*Close-in Design Range*	Far Design Range		Close-in Design Range	
	f'_{dc}/f'_c	f'_{dc}/f_c	f_{dy}/f_y	f_{du}/f_u	f_{dy}/f_y	f_{du}/f_u
Bending	1.19	1.25	1.17	1.05	1.23	1.05
Diagonal Tension	1.00	1.00	1.00	1.00	1.10	1.00
Direct Shear	1.10	1.10	1.10	1.00	1.10	1.00
Bond	1.00	1.00	1.17	1.05	1.23	1.05
Compression	1.12	1.16	1.10	1.00	1.13	1.00

The Unified Facilities Criteria (2008) expresses the dynamic design stress as the product of the static stress (yield or ultimate) and the DIF. The dynamic strength may also include the strength increase factor (SIF) as per Equation 2 and Equation 3.

[2] $$f_{dy} = f_y \times DIF \times SIF$$

[3] $$f_{du} = f_u \times DIF \times SIF$$

While a DIF values may be determined from tables, the use of numerical models, such as those developed by Soroushian and Choi (1987), Malvar and Crawford (1998), and the Comité Euro-International du Béton (1988) will provide more accuracy in design of reinforced concrete elements under blast loading. The strain rates in reinforced concrete members under blast loading is not constant and depends on the location of element relative to centre of explosion. Thus equations providing DIF values dependant on strain rate yields more accurate values than tabulated values.

2.3 Effect of Dynamic Loads on Bond of Reinforcing Steel to Concrete

While a number of researchers have actively investigated the effects of dynamic loading on concrete and steel properties, the interaction between the two materials under dynamic loading has been neglected. The level of increase in material strength under high strain rates such as those produced by blasts and impact loading is different for concrete and reinforcing steel. As a result, predicting the interaction at the steel-concrete interface becomes a very intricate problem involving many factors.

Some research has been conducted to investigate the steel reinforcement-concrete bond under high strain rates using direct pullout testing. These research efforts (Shah 1963, Vos and Reinhardt 1982, Yan and Mindess 1991, Weathersby 2003) have demonstrated that the bond strength is higher under dynamic loading. Pullout testing, however, causes a compressive stress in concrete surrounding the reinforcement at the support location and leads to greater confinement and increase in bond strength (Weathersby 2003). When dealing with beams in flexure, the concrete surrounding the reinforcement may be in tension and in a cracked state. Thus pullout testing might not be representative of bond behaviour in flexural elements such as beams and columns. According to Shah (1963), greater accuracy in bond strength tests could be achieved by beam tests rather than direct pullout tests.

Existing literature on the effect of strain rate on bond strength in beams is limited. While some investigators have shown little or no increase in bond strength at high loading rates from pullout testing, the conservatism of these tests may be limited because of the influence of the high confining stresses. A more accurate approach may be achieved by conducting flexural tests, which provide more realistic measures of bond strength in reinforced concrete beams.

3 Objective of Research

In order to advance the current level of knowledge in blast resistance of reinforced concrete structures, an experimental program was designed to investigate the bond strength of steel reinforcement in reinforced concrete beams under short duration blast loading. The objectives of the research were to study the steel reinforcement-concrete bond under high strain rate, investigate the adequacy of the development length calculated in accordance with the Canadian Standard for Concrete Structures (CSA 2004) in resisting blast loading, and proposing dynamic increase factors for bond in blast resistant design.

4 Experimental Program

The experimental program consisted of reinforced concrete beams with three different sizes of reinforcement: 15M, 20M, and 25M. Only the results of the testing involving the 20M steel reinforcement are presented in this paper. The results from the entire research program are presented elsewhere (Toikka 2012).

Each beam was designed with one reinforcing bar bonded to the concrete for the bar development length calculated in accordance with CSA A23.3-04 (2004). The primary objective of the experimental test program was to determine whether the development length provided for static loading is sufficient for beams under high strain rates.

4.1 Description of Test Specimens

Figure 1 presents the dimensions and details of the reinforced concrete beams. Each beam had an overall length of 2440 mm and a cross-sectional dimension of 170×220 mm and reinforced in shear with 6-mm diameter reinforcing wire spaced at 100 mm at the ends, within the development length, and 150 mm in the middle. The reinforcing bar was debonded in the middle to achieve a bonded length at either end equal to the development length specified by CSA A23.3-04 (2004). For the 20M steel bars the development length was calculated to be 523 mm.

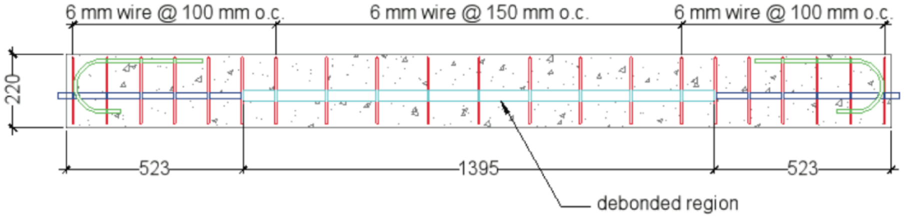

Figure 1: Dimensions and details on reinforced concrete beams

4.1.1 Material Properties

All beams were cast from the same concrete mix. A 28-day strength of concrete compressive strength of 30 MPa, and aggregate size of 10 mm were specified and supplied by a local concrete supplier. Concrete cylinders were cast with the beams and tested in accordance with ASTM C873 (2010) to obtain compressive strength of concrete. The concrete compression tests were performed at the time of testing and resulted in an average compressive strength of 37.0 MPa.

The steel reinforcement was cut to a length of 2440 mm using a hand saw and used as longitudinal reinforcement in the concrete beams. Steel samples were also cut and tested in tension in accordance with ASTM A370-11a (2011) to obtain the yield stress, ultimate stress and stress-strain behaviour of the reinforcement at a static strain rate of about 30×10^{-6} 1/s. From the test results, the average yield strength of the 20M bars was 437 MPa, and the yield strain was 2408×10^{-6} mm/mm. The steel specimen was also tested at higher loading rates of about 0.20 1/s and 0.10 1/s. The strength and strain characteristics obtained from the high strain rate testing are presented in Table 2 along with DIF value achieved for each strain rate.

Table 2: DIF values for 20M reinforcing steel used in experimental program

Strain Rate (1/s)	**Rebar Size**	**Yield Strength (MPa)**	**Ultimate Strength (MPa)**	**Strain at Yield Strength (mm/mm)**
Static	20M	437.3	656.0	0.002408
0.1 strain/s		480.3	719.6	0.002462
DIF		***1.10***	***1.10***	***1.02***
0.2 strain/s		478.0	726.9	0.002837
DIF		***1.09***	***1.11***	***1.18***

4.2 Static Testing

Static testing was performed on the beams using a hydraulic jack equipped with a hand pump (Figure **2**). The jack was placed on top of a spreader beam which applied two point loads to the beam at third-points.

The beams were loaded at an approximate rate of 20 kN/min. Each beam was loaded past the yield point of the reinforcement and up to failure in order to determine strains along the bonded region at the yield and ultimate capacity of the concrete beam.

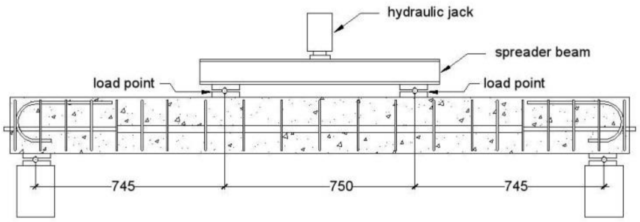

Figure 2: Static Test Setup

4.3 Dynamic Testing

4.3.1 Shock Tube

The shock tube located in the Structural Engineering Laboratory of University of Ottawa was used to generate short-duration shock loading used for the dynamic tests. The shock tube is capable of simulating the effect of real explosion from a given explosive charge mass and standoff distance on structural elements. In order to understand how the shock tube simulates blast loads, a brief description of its assembly and mechanisms is outlined below.

The shock tube consists of driver, spool, and expansion sections. The driver is at the back of the shock tube and has a variable length. The driver length affects the positive phase duration of the blast wave while the driver pressure affects the amplitude of the shock wave. The driver length and pressure in this experimental program were selected to achieve the desired blast wave parameters. Next to the driver section is a spool section, separated from the driver section by double diaphragm firing mechanism which controls the pressure wave release of the shock tube.

Ahead of the spool section is the expansion section, which connects to the end frame used for loading the specimen. Once the pressure is released from the driver, it expands and forms a shock wave as it travels through the expansion section. When the wave reaches the end of the expansion area, it acts on the end frame and a specially designed load transfer device (LTD) loads the concrete beam being tested. Detailed description of the shock tube's construction, initiation of the firing mechanism, and calibration is presented elsewhere (Lloyd 2010).

4.3.2 Shock Tube Testing

For each beam test, the LTD was assembled onto the end frame and attached to the concrete beam to exert third-point loading (Figure 3). The LTD is comprised of two rigid steel panels; 2032 mm tall by 1000 mm wide and placed side-by-side. These rigid steel panels were fastened to sliding hinges, allowing the LTD to deflect when subject to a blast load. Once both rigid steel panels were secured onto the hinges the shock tube opening was completely covered. Two steel beams were attached to the rigid steel panels. The entire LTD weighed 283.6 kg and was capable of a maximum lateral movement of 200 mm.

After installing the LTD, the beam was placed vertically against it and fastened to the LTD, at the top and bottom, by clamping the beam between two steel sections with a threaded rod. These steel sections had a steel rod welded to its surface to ensure simply supported conditions.

5 Data Acquisition

During testing, all data was recorded to a computer-based data acquisition system. The strains in the reinforcement and beam midspan and load point displacements were measured with strain gauges and linear variable displacement transducers (LVDT's) respectively.

The strain gauges were installed before casting of the concrete: 2 gauges in the debonded region and 4 gauges along the development length on both sides of the debonded region as shown in Figure 4.

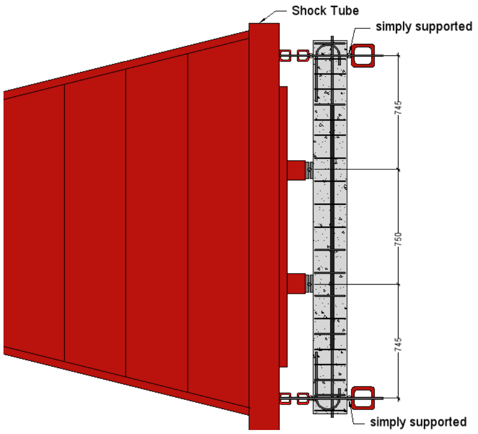

Figure 3: Beam setup on Shock Tube for dynamic testing

LVDT’s were also attached to the protruding ends of the longitudinal reinforcement in the beam to record slippage between the reinforcement and concrete. A high-speed camera was used to observe the behaviour of the beams under blast loads induced by the shock tube. The high-speed camera was placed perpendicular to the face of the frame so as to observe lateral deflections of the beam during testing.

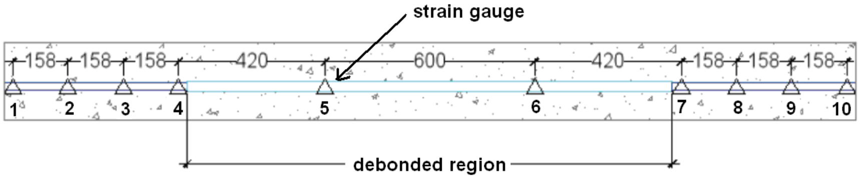

Figure 4: Strain gauge locations along 20M steel reinforcement

6 Results of Experimental Program

6.1 Static Results

Typical load-deflection response of beams with 20M reinforcement tested under static loading is presented in Figure 5. The maximum capacity of the beam was 26.9 kN. The deflection at the midspan and load point at maximum capacity of the beam was 34.8 mm and 23.6 mm respectively with a corresponding support rotation of 1.81°.

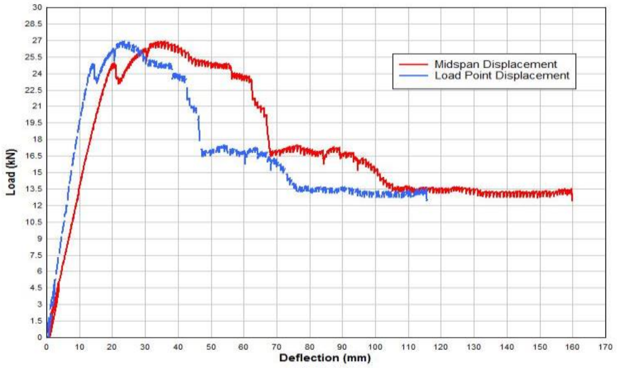

Figure 5: Typical load–displacement response

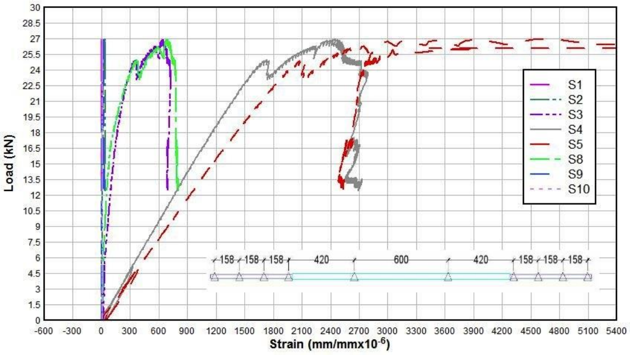

Figure 6: Typical load versus strain response

Strains along the 20M reinforcement are shown in Figure 6. No change in strain was observed at the strain gauges farthest from the debonded region and no slip recorded at the ends of the rebar. This indicates the development length required for the 20M rebar is less than the bonded length of 523 mm. Due to the strain gauge spacing, the development length is estimated between 500 mm and 340 mm.

6.2 Dynamic Results

The driver length used for the shock tube testing was 1219 mm. The driver pressure was varied between tests to achieve different strain rate effects in the beams. Yielding of 20M size rebar under dynamic loads was experimentally determined in the ancillary testing to be 2650×10^{-6} mm/mm This strain represents the average yield strain from tests performed at 0.10 and 0.20 1/s). In order to ensure the yield strain was achieved, several shock tube tests were conducted on the first beam in order to determine the driver pressure that would result in yielding of the 20M reinforcement, and that could be used for subsequent tests on virgin specimens. From the results of the first beam, a driver pressure of 227 kPa was determined to cause yielding of the 20M reinforcement. As a result, this pressure was used for first test on subsequent beams. A second test with greater driver pressure was also performed on the beams to cause severe yielding in the reinforcement.

Figure 7 and Figure 8 present typical results of dynamic test on the concrete beams with a driver pressure of 227 kPa. The test resulted in a reflected pressure of 42.6 kPa and a reflected impulse of the positive phase of 216.2 kPa-ms. The positive phase duration was 11.5 ms. The maximum midspan and load point displacements of the beam were 44.9 mm and 30.3 mm respectively, occurring at 24.7 ms. The corresponding support rotation was 2.33°. No reinforcement slip was recorded at either end of the beam.

The strain rate in the reinforcing steel was 0.202 1/s while the maximum strain in the debonded region was 2933×10^{-6}, recorded in gauge S5 at 23.6 ms. Gauges S1, S9, and S10 did not experience significant strain changes, only small oscillations. The dynamic development length was determined to be between 340 mm and 500 mm, which is less than 523 mm provided.

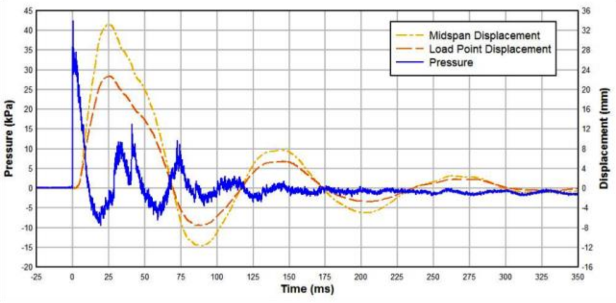

Figure 7: Typical pressure and displacement profiles of shock tube testing

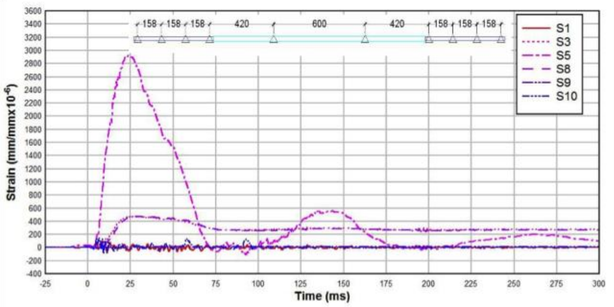

Figure 8: Typical reinforcement strain profiles of shock tube testing

6.3 Comparison of Static and Dynamic Tests

The strain profile was plotted for when the strain in the debonded region had reached the yield strain in either the static and dynamic tests (Figure 9). The yield strains used were those determined in the ancillary static test and shock tube test. The yield strain was chosen since the main purpose of the experimental program is to determine whether current standards for calculating the development length are sufficient for blast design. Since the development length is a function of the yield strain and yield stress, the strain profile at the time when steel reached its yield strength is of utmost importance.

For the tests on 20M reinforcement, the static yield strain was 2408×10^{-6} mm/mm while the dynamic yield strain was 2650×10^{-6} mm/mm. The strain profile under dynamic loading results in lower values along the bonded regions in comparison to the static strain profile (Figure 9). Shot 1 with a strain rate of 0.1976 1/s shows the lowest strain in the bonded region resulting in the highest bond stress. Shot 2 is with a strain rate of 0.3440 1/s, shows lower bond stress in comparison with shot 1 because this test was carried on the same beam after shot 1 and it is likely that shot 1 had caused some level of damage on the beam prior to the second test.

A summary of the data from the static and dynamic testing of reinforced concrete beams showed consistent behaviour among the beams. The test results showed higher bond stress under high strain rate resulting in shorter development lengths. The development length under shock tube testing was less than that calculated in accordance with CSA A23.3 (2004).

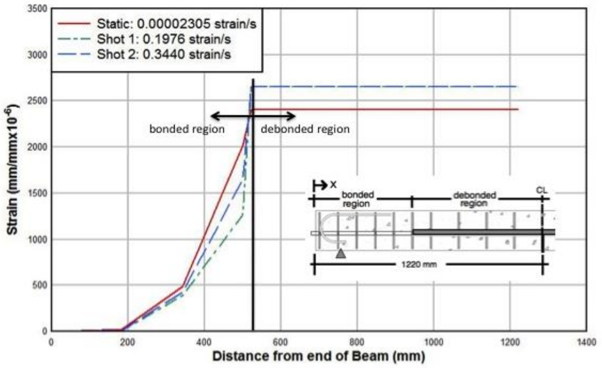

Figure 9: Comparison of strain along bonded region for static and dynamic tests

7 Analysis of Results

The bond stress, μ, may be calculated by the following equation (ACI Committee 408, 2003):

[4] $$\mu = \frac{\Delta f_s d_b}{4 \Delta l}$$

Where Δf_s is the change in tensile stress in the reinforcing steel, d_b is the diameter of the reinforcing steel, and Δl is the distance between points on the steel over which the change in bar stress occurs.

This equation was used with the data obtained from static and dynamic testing to calculate the bond stress between the locations of two strain gauges on the steel reinforcement. The bond stress was calculated at the time when the steel in the debonded region reached the yield strain for both static and dynamic tests. The stress at each point was determined by equation [5].

[5] $$f_s = \varepsilon_s E_s$$

Where ε_s is the strain in the steel and E_s is the modulus of elasticity of steel (assumed to be 200 GPa). Due to the fact that the bond stress reached a strain very close to zero in strain gauges 2 and 7, it was assumed the force in the steel was completely transferred to the concrete by the time it reached these gauges. The results from calculating the bond stress between the gauges are shown in Table 3 where SB and DB denote the static and dynamic test beams respectively. The DIF for bond stress was calculated to be 1.71.

Table 3: Bond Stress in 20M Reinforcing Steel

Gauges	Distance (mm)	SB-20M-1 ×10^{-6} (mm/mm)	SB-20M-2 × 10^{-6} (mm/mm)	Average Static Strain ×10^{-6} (mm/mm)	Average Static Bond Stress (MPa)	DB-20M-2-1 × 10^{-6} (mm/mm)	DB-20M-3-1 × 10^{-6} (mm/mm)	Average Dynamic Strain × 10^{-6} (mm/mm)	Average Dynamic Bond Stress (MPa)	DIF
S1 and S10	26	0	0	0		0	0	0		1.71
S2 and S9	184	20	19	19	0.12	8	4	6	0.04	
S3 and S8	342	484	566	525	3.12	377	409	393	2.39	
S4 and S7	500	2014	2008	2011	9.17	1543	995	1269	5.40	
S5 and S6	523	2408	2407	2407	16.78	2650	2651	2651	58.59	
					9.69				16.60	

8 Conclusions

An experimental program was designed to investigate the high strain rate effects on steel reinforcement-concrete bond and to verify the adequacy of the development length required by the CSA A23.3-04 (2004) for blast load resistance. Steel reinforced concrete beams with steel reinforcement bonded over the development length calculated in accordance with CSA A23.3 (2004) were tested under static and shock tube (dynamic) loading. The steel reinforcement was instrumented with strain gauges to monitor reinforcement strains during testing.

The following conclusions can be drawn from the experimental program:

- The bond stress between concrete and steel increases with increased strain rate.
- Development length of steel reinforcement required to develop the dynamic yield strength is less than that required to develop the static strength of steel reinforcement.
- The equation used to determine the development length required for static loads is sufficient for calculating the development length at high loading rates.
- The DIF for bond stress observed from the test program was 1.71.

9 Recommendations

Even though the experimental program was carefully designed to provide development length, the number of strain gauges limited the accuracy of the development length measurement. Also, because the development length provided was adequate to develop the dynamic yield stress, the development length under high strain rate was not determined. Thus the following recommendations for future research are made:

- Provide more strain gauges at closer spacing along the bonded region of reinforcing steel to obtain a more detailed and accurate strain profile.
- Construct beams with a shorter debonded region. This will allow higher strains to be achieved in the steel reinforcement and the strain profile at high levels of strain to be analyzed.
- Investigate the effect of steel strength on the increase in bond stress. This can be achieved by testing beams of the same size reinforcement, but providing different strengths.
- Investigate the effect of reinforcement size on the increase in bond stress under high strain rate.

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