Building Tomorrow's Society

Bâtir la Société de Demain

Fredericton, Canada

June 13 – June 16, 2018/ *Juin 13 – Juin 16, 2018*

SHEAR BEHAVIOUR OF CAST-IN-PLACE ANCHORS AT LOW AND HIGH STRAIN RATES

Ahmed, Lenda T.[1,2] and Braimah, Abass[1]
[1]Carleton University, Canada
[2]lendaalsaeab@cmail.carleton.ca

Abstract: The use of anchorage to concrete systems in construction is on the rise. Moreover, the anchorage to concrete systems are subjected to various loading conditions; including static, dynamic and shock. However, limited information is available on the behaviour of anchorage to concrete systems under impact and high strain rate loading. This paper presents the shear behaviour of cast-in-place anchorage to concrete systems using finite element analysis. Cast-in-place anchors were embedded in concrete with compressive strengths of 20 MPa, 30 MPa and 40 MPa were investigated at static (10^{-5} s^{-1}) and high strain rate (10^{3} s^{-1}). The anchorage systems used two anchor diameters (12.7 mm and 19.1 mm) and two embedment depths (76.2 mm and 152.4 mm). The analyses results show that the ultimate shear load increased with the strain rate for the same concrete compressive strength. The increase in compressive strength led to increase in the ultimate shear load for the anchors tested when pryout failure mode was the dominant failure mode. A maximum ultimate shear load increase of 40.8% was achieved for concrete compressive strength increase from 20 MPa to 40 MPa at strain rate of 10^{-5} s^{-1}. At high strain rate of 10^{3} s^{-1} maximum increase in the ultimate shear load of 2.7% was obtained for concrete compressive strength increase from 20 MPa to 40 MPa. Increase in the anchor diameter and embedment depth was also observed to increase the ultimate shear load. As well, the anchorage to concrete system failure mode was influenced by increase in strain rate while the increase in concrete compressive strength from 20 MPa to 40 MPa had no effect on the failure mode at high strain rate where steel failure is observed.

Keywords: Cast-in-place anchor, Concrete compressive strength, Strain rate, Shear load, Finite element analysis, Shock and Blast load.

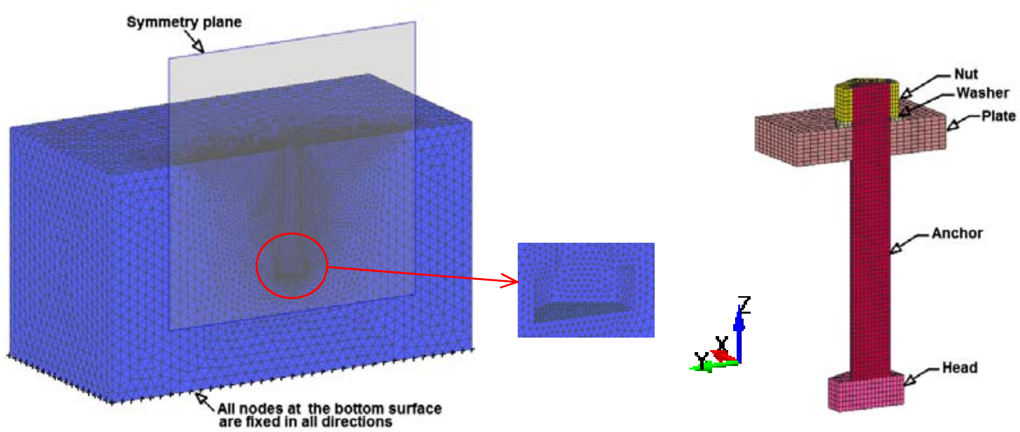
1 INTRODUCTION

Cast-in-place anchors are widely used in many applications including in nuclear power plants, bridge and building construction. Anchorage systems are exposed to shear, tensile and combined loads that can be either static or dynamic such as seismic, impact and blast loading. There are two main categories of anchorage to concrete systems: cast-in-place and post-installed anchorage systems. Factors such as effect of edge distance, anchor diameter, embedment depth and anchor spacing on the shear behaviour of the anchors have been investigated by several researchers (Ueda et al. 1991, Lee et al. 2011, Alqedra and Ashour 2005). Shear behaviour of cast-in-place anchor under static load was investigated by Jebara et al. (Jebara et al. 2016). Gross et al. and Muratli et al. investigated static and dynamic concrete breakout shear capacity of cast-in-place and post-installed anchors. The authors found that the dynamic breakout shear capacity is higher than the static capacity of the anchors tested (Gross et al. 2001, Muratli et al. 2001). Nilforoush et al. investigated effect of concrete compressive strength on the tensile behaviour of cast-in-place anchors and stated that the increase in the concrete compressive strength increased the tensile capacity of cast-in-place anchors (Nilforoush et al. 2017). Similar observation was reported by Sakla and Ashour on adhesive anchors (Sakla and Ashour 2005). However, limited research is available in the

literature on the shear behaviour of anchors embedded in different concrete strength and tested at high strain rates.
Research focusing on the effect of dynamic loads such as impacts and blasts on anchorage to concrete system is limited and far less than that on the concrete and steel materials. Ross et al., Georgin and Reynouard and Min et al. conducted numerical analysis on the effect of strain rate on the strength of the concrete. The authors observed that the increase in the strain rate increased the concrete compressive strength (Ross et al. 1995, Georgin and Reynouard 2003, Min et al. 2014). Yu et al. and Hopperstad et al. studied the effect of strain rate on the behaviour of steel. The authors concluded that the increase in the strain rate increased the strength of the steel (Yu et al. 2009, Hopperstad et al. 2003).
Predicting the anchorage response under high dynamic loading is necessary to ensure structural safety and to minimize or prevent anchorage failure. In addition, there is a need to investigate effect of high strain rates on the shear capacity of the cast-in-place anchors embedded in different concrete compressive strength. Effect of strain rate, concrete compressive strength, anchor diameter and embedment depth on the shear capacity and failure mode was investigated.

2 FINITE ELEMENT MODELING AND BOUNDARY CONDITION

Shear behaviour of cast-in-place anchors at low and high strain rates was investigated using LS-DYNA finite element software package (Livermore software technology Corporation 2012). Steel anchor, nut, washer and anchor plate were modeled with eight-noded hexahedron solid elements. Concrete was modeled with four noded tetrahedron solid elements. Single cast-in-place anchor is placed in the center of the concrete block and used for the analysis. Concrete block size of ($2h_{ef}$ +150) × ($2h_{ef}$ +150) × ($1.5h_{ef}$ +50) mm was used to eliminate effect of concrete edge on the behaviour of the anchors. Anchor diameters of 12.7 mm and 19.1 mm were investigated. The bottom surface of the concrete block is restrained from translational and rotational movement during the loading. *BOUNDARY_PRESCRIBED_MOTION_SET in y-direction was applied on the anchor plate to model the shear load. Due to symmetry of the anchorage system and in order to increase the efficiency and reduce the computational time, half of anchorage to concrete was modeled. Symmetry plane boundary condition (YZ-plane) was applied. *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE was used to model the interaction between the various parts of the anchorage system. Figure 1 shows the geometry and boundary condition of the cast-in-place anchor model.



(a) concrete mesh (b) cast-in-place anchor mesh

Figure 1: Geometry and boundary condition of cast-in-place anchor model

The concrete was modelled using Continuous surface Cap Model (MAT_159). MAT_159 is characterized by simple input parameters and able to represent concrete behaviour including damage and strain rate effect (Wu et al. 2012, Bermejo et al. 2011). LS-DYNA has a built in parameter (IRATE) to represent the strain rate effect on the concrete strength by setting it equal to unity. By using IRATE formulation, the

increase in the strain rate increases the strength of the concrete material (Murray 2007). The density and compressive strengths of the concrete were 0.0024 g/mm^3 and (20, 30, 40) MPa, respectively.
The steel for the anchor, washer, plate and nut was modeled using Piecewise Linear Plasticity Model (MAT_024). Cowper-Symonds parameters C of 40 s^{-1} and P of 5 were used to represent the strain rate effect on the steel material (Boh et al. 2004). The properties of the steel anchor were in accordance with ASTM A354 specification with yield strength of 896 N/mm^2, ultimate tensile strength of 1034 N/mm^2, failure strain of 14%, Young's modulus of 200000 N/mm^2 and density of 0.00785 g/mm^3.

3 COMPARISON OF FINITE ELEMENT RESULTS WITH DESIGN METHODS

When the anchors are installed far from the concrete free edge and subjected to shear loading, pryout failure and or steel anchor failure are the dominant failure modes. The pryout failure load of the anchor can be calculated according to ACI 318 (Eq. 1 and Eq. 2) (ACI Committee 318 2011). The steel anchor failure can be calculated as in (Eq.3) (ACI Committee 318 2011).

[1] $V_{cp} = k_{cp}\, N_{cb}$

[2] $N_{cb} = 15.5\,\sqrt{f'_{cc}}\, h_{ef}^{1.5}$

[3] $V_{uo} = 0.6\, A_s \cdot F_{ut}$

Where
k_{cp} is a modification factor for embedment depth effect, k_{cp} equal one for embedment depths less than 63.5 mm and two for the embdment depths equal to or gretaer than 63.5 mm. N_{cb} is the concrete tensile breakout capacity for the anchor, f_{cc} is the concrete cube compressive strength, h_{ef} is the embedment depth, A_s is the effective cross sectional area of the anchor, F_{ut} is the ultimate tensile strength of the anchor.

Concrete cube compressive strengths of 25 N/mm^2, 37 N/mm^2 and 50 N/mm^2 are equivalent to concrete compressive strengths of 20 N/mm^2, 30 N/mm^2 and 40 N/mm^2 respectively and used in Eq. 2 (British Standards Institution Draft for development 1992, British Standards Institution 2013, Committee Euro-International du Beton (CEB) 1994).

Table 1 presents a comparison of ultimate shear load obtained from the finite element analysis (FEA) and ACI-318 (ACI Committee 318 2011) for the two anchor diameters. The failure mode observed from the finite element analysis is also presented in the Table. Minimum value of the ultimate shear load obtained from Eq. 1 and Eq. 3 is considered for comparison with the finite element results and included in Table 1. As shown in the Table, the shear load calculated by the ACI-318 method is in a good agreement with the finite element analysis, especially for the 19.1 mm anchor diameter.

Table 1: Comparison between FEA and ACI-318

d (mm)	f_c' (N/mm²)	h_{ef} (mm)	Failure Load (kN)		FEA/ ACI-318	*Failure mode (FEA)
			FEA static	ACI-318		
12.7	20	76.2	72.28	78.59	0.92	PR
	30	76.2	86.64	78.59	1.10	S
	40	76.2	88.20	78.59	1.12	S
	20	152.4	88.87	78.59	1.13	S
	30	152.4	90.16	78.59	1.15	S
	40	152.4	91.17	78.59	1.16	S
19.1	20	76.2	101.72	103.10	0.99	PR
	30	76.2	124.18	125.43	0.99	PR
	40	76.2	143.25	145.81	0.98	PR
	20	152.4	158.31	177.75	0.89	PR
	30	152.4	174.09	177.75	0.98	S
	40	152.4	177.33	177.75	1.00	S

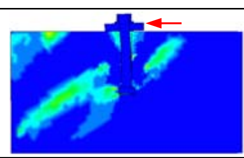
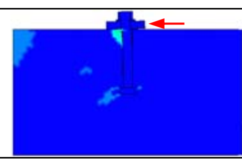
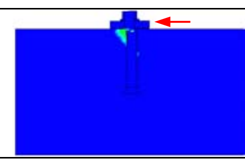
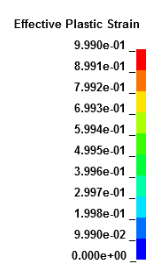
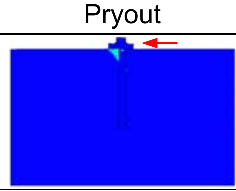
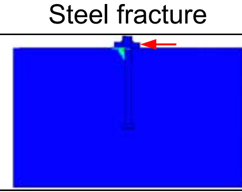
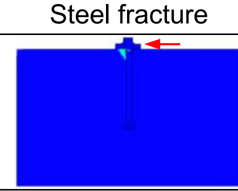
*Failure mode: PR: pryout, S: steel failure

4 RESULTS AND DISCUSSION

4.1 Failure Mode

Shear behaviour of cast-in-place anchors subjected to low strain rate ($\dot{\varepsilon}$) of 10^{-5} s^{-1} and high strain rate of 10^{3} s^{-1} was investigted. Low strain rate for static loading is in the range from 10^{-6} s^{-1} to 10^{-5} s^{-1}. Low dynamic and earthquick strain rates are in the range from 10^{-4} s^{-1} to 10^{-1} s^{-1}. Strain rate for impact loading is in the range between 10^{0} s^{-1} to 10 s^{-1}, while very high strain rate ranging from 10^{2} s^{-1} to 10^{3} s^{-1} is related to blast loading (Bischoff and Perry, 1991).

Figures 2 and 3 show the failure mode of the 12.7-mm and 19.1-mm diameters cast-in-place anchor respectively with concrete compressive strengths of 20 MPa, 30 MPa and 40 MPa at low and high strain rates of 10^{-5} s^{-1} and 10^{3} s^{-1}. As shown in Figure 2, at low strain rate of 10^{-5} s^{-1}, pryout failure mode is observed for the concrete compressive strength of 20 MPa and embedment depth of 76.2 mm. Steel anchor failure is observed for the concrete compressive strengths of 30 MPa and 40 MPa. Also, steel anchor failure is observed for the embedment depth of 152.4 mm at all concrete compressive strengths. At strain rate of 10^{3} s^{-1} steel anchor failure is observed for all the concrete compressive strengths and embedment depths investigated.

<table>
<tr><th>$\dot{\varepsilon}$ (s^{-1})</th><th>h_{ef} (mm)</th><th>f_c' =20 MPa</th><th>f_c' =30 MPa</th><th>f_c' =40 MPa</th><th></th></tr>
<tr><td rowspan="4">10^{-5}</td><td rowspan="2">76.2</td><td></td><td></td><td></td><td rowspan="4">
</td></tr>
<tr><td>Pryout</td><td>Steel fracture</td><td>Steel fracture</td></tr>
<tr><td rowspan="2">152.4</td><td></td><td></td><td></td></tr>
<tr><td>Steel fracture</td><td>Steel fracture</td><td>Steel fracture</td></tr>
</table>

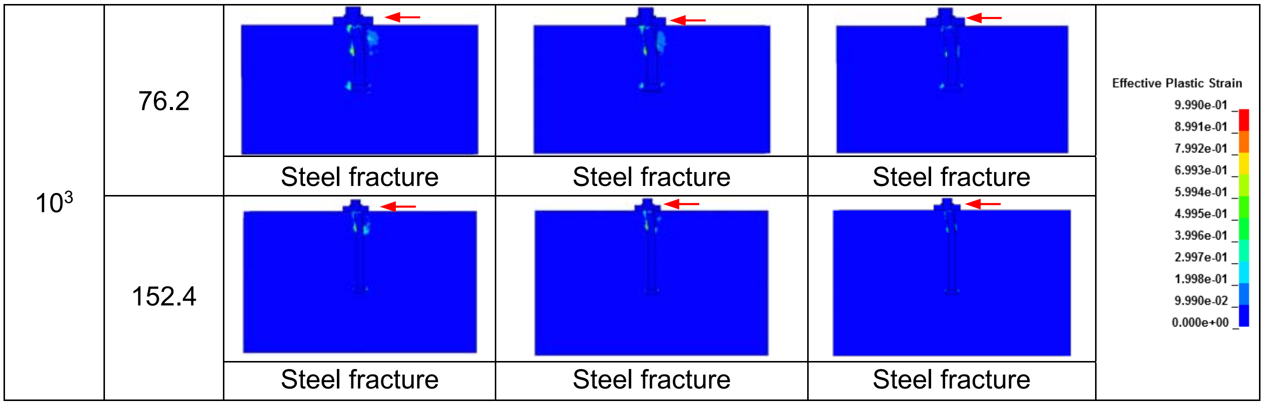


Figure 2: Effect of strain rate and concrete compressive strength on the failure mode for the 12.7 mm diameter cast-in-place anchors

As shown in Figure 3, at low strain rate of 10^{-5} s^{-1}, pryout failure is observed for the compressive strengths of 20 MPa, 30 MPa and 40 MPa at embedment depth of 76.2 mm. For the anchor embedment depth of 152.4 mm pryout failure is observed for the compressive strength of 20 MPa while steel failure is observed for the compressive strengths of 30 MPa and 40 MPa. At high strain rate of 10^3 s^{-1} steel anchor failure is observed for the concrete compressive strengths and embedment depths investigated. The increase in the embedment depth showed an increased shear capacity when the pryout failure mode is the dominant (Figure 5).

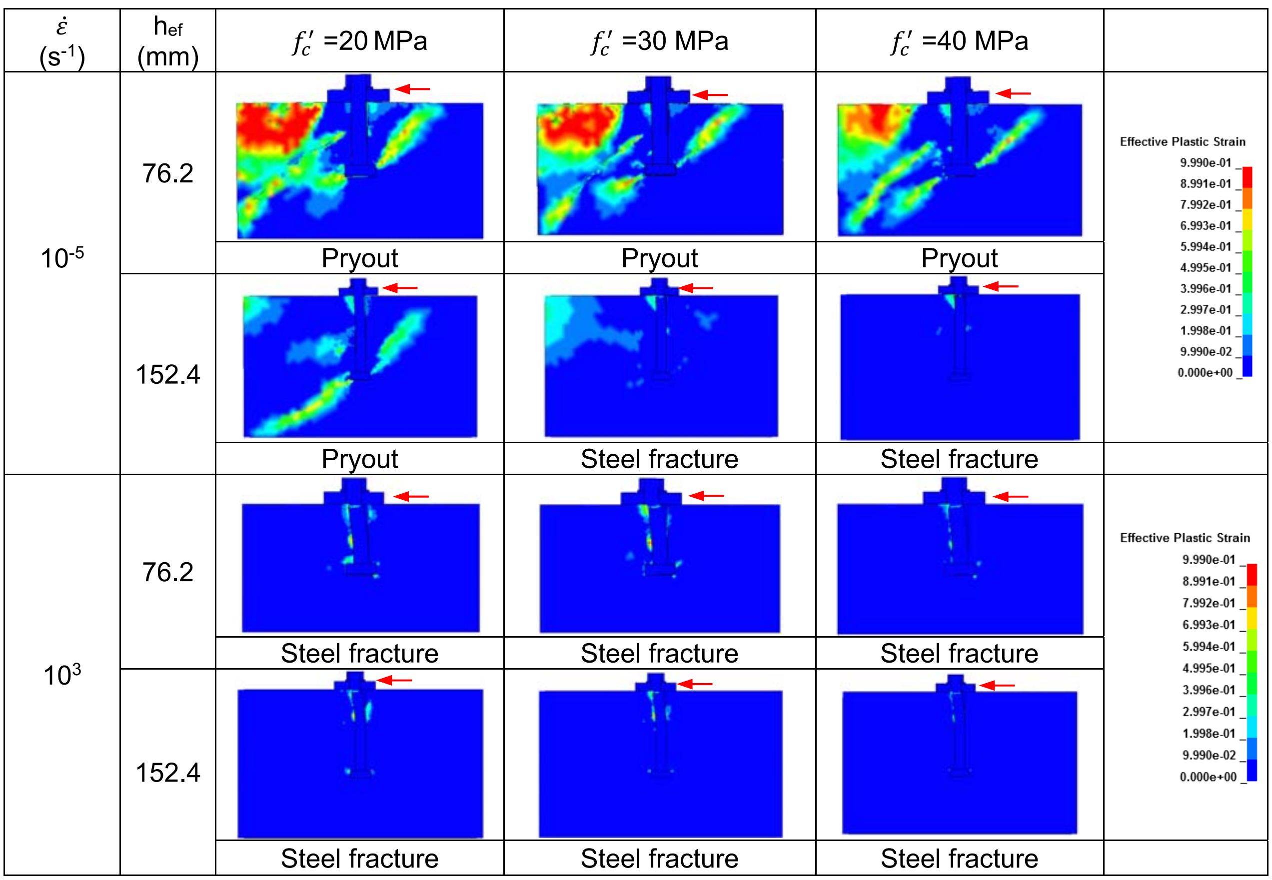
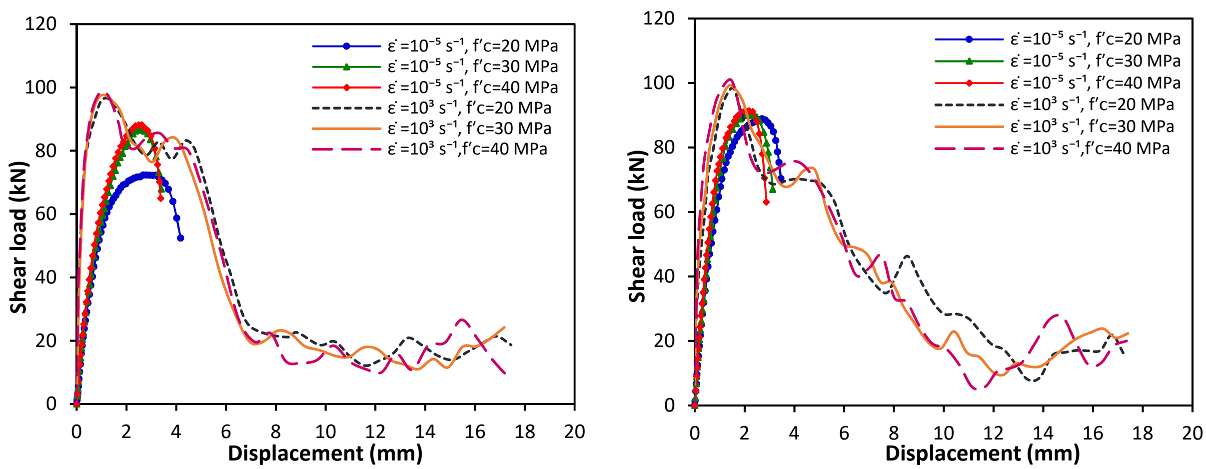


Figure 3: Effect of strain rate and concrete compressive strength on the failure mode for the 19.1 mm diameter cast-in-place anchors

From Figures 2 and 3, it can be stated that at low strain rate of 10^{-5} s^{-1}, the failure mode is influenced by the concrete compressive strength. However, at high strain rate, the anchorage failure mode transitions to steel failure thus no influence of concrete compressive strength on the failure mode of the cast-in-place anchor was observed. More severe concrete cracking was observed for the cast-in-place anchors embedded in 20 MPa concrete compressive strength than that embedded in 30 MPa and 40 MPa concrete compressive strengths. At high strain rate, it can be seen that the damage extends to a small area in the concrete where anchor bending followed by fracturing is observed.

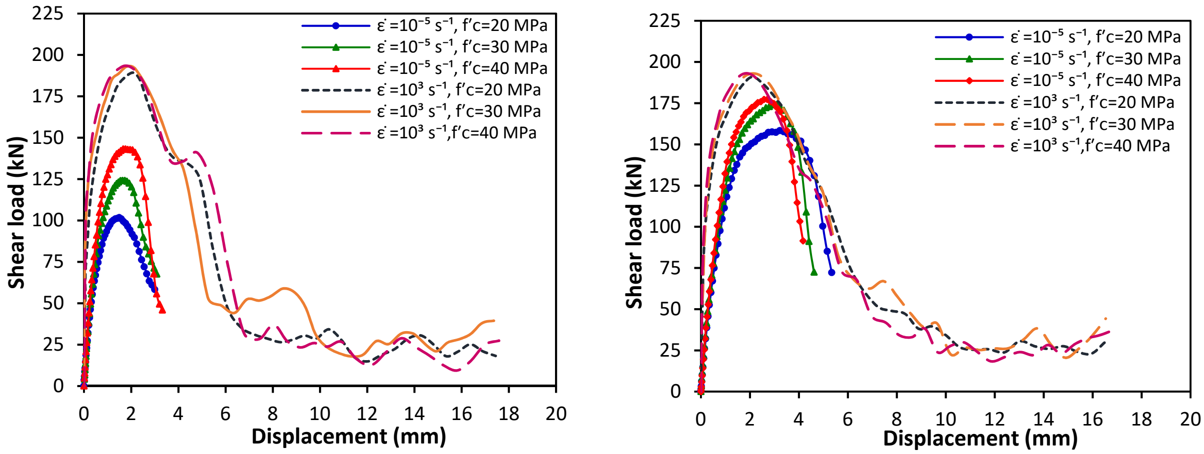
4.2 Effect of Strain Rate

Shear behaviour of cast-in-place anchors was investigated using LS-DYNA finite element software. Anchor diameters of 12.7 mm and 19.1 mm with embedment depths of 76.2 mm and 152.4 mm were investigated at low and high strain rates of 10^{-5} s^{-1} and 10^{3} s^{-1}. Three concrete compressive strengths of 20 MPa, 30 MPa and 40 MPa were selected for the analysis to investigate the effect of concrete strength on the shear response of cast-in-place anchors. Figures 4 and 5, show the effect of concrete compressive strength on the load-displacement response of the 12.7-mm and 19.1-mm diameters cast-in-place anchor respectively. As shown in Figures 4 and 5, at low strain rate of 10^{-5} s^{-1}, the shear load of the cast-in-place anchors increased with the displacement until the maximum load then it decreased till failure. Concrete compressive strength of 40 MPa resulted in higher shear load compared to the concrete compressive strength of 20 MPa. Similar observation was reported by Çalışkan et al. on the adhesive anchors embedded in low strength concrete of 5 MPa and 10 MPa and subjected to cyclic shear load (Çalışkan et al. 2013). At low strain rate, the increment in the shear load is found to be higher at the shallow embedment depth of 76.2 mm, where pryout failure is observed, compared to deeper embedment depth of 152.4 mm where the failure mode was by steel fracture. At high strain rate of 10^{3} s^{-1}, the load increased with the displacement until the ultimate value, and then sharply decreased with increased displacement until failure. The increase in the strain rate from 10^{-5} s^{-1} to 10^{3} s^{-1} resulted in increased shear capacity.



(a) embedment depth of 76.2 mm (b) embedment depth of 152.4 mm

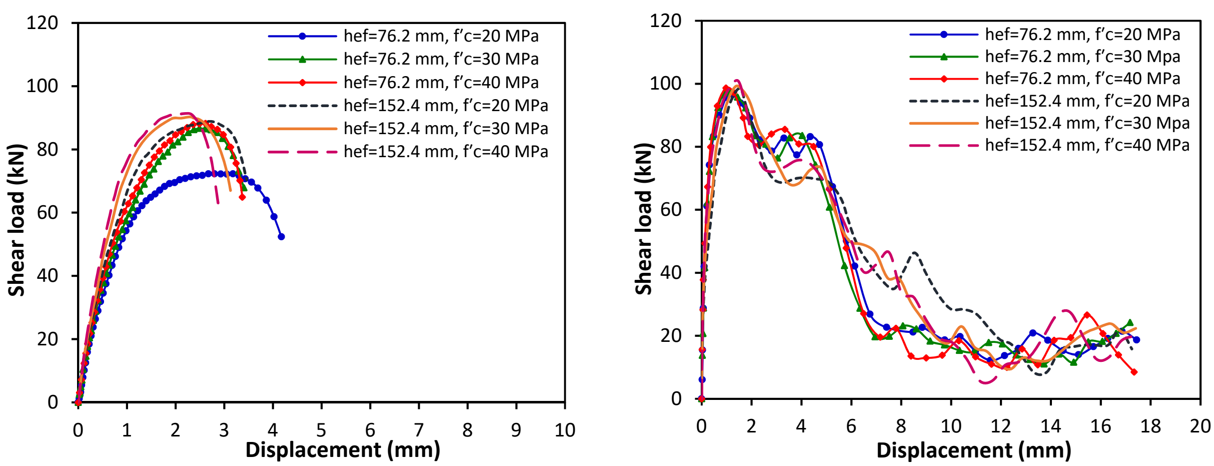
Figure 4: Shear load-displacement response of 12.7 mm cast-in-place anchor diameter at low and high strain rates



(a) embedment depth of 76.2 mm (b) embedment depth of 152.4 mm

Figure 5: Shear load-displacement response of 19.1 mm cast-in-place anchor diameter at low and high strain rates

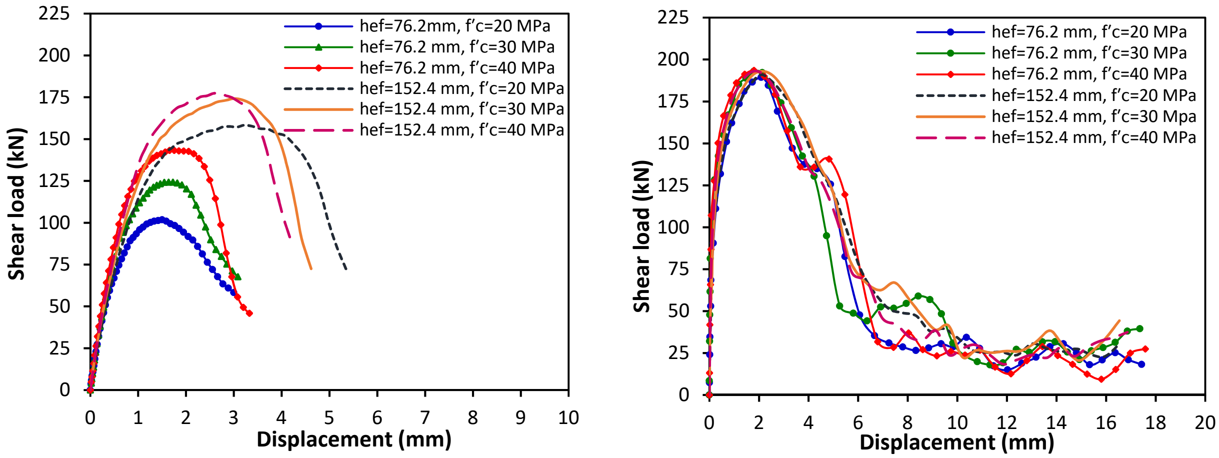
Figures 6 and 7 show the effect of embedment depth on the shear behaviour of the 12.7 mm and 19.1 mm diameters cast-in-place anchor respectively embedded in concrete compressive strengths of 20 MPa, 30 MPa and 40 MPa.



(a) Strain rate of 10^{-5} s^{-1} (b) Strain rate of 10^{3} s^{-1}

Figure 6: Effect of embedment depth on the shear load-displacement response of 12.7 mm cast-in-place anchor diameter at low and high strain rates

From Figure 6, it can be seen that at low strain rate of 10^{-5} s^{-1} the increase in the anchor embedment depth from 76.2 mm to 152.4 mm increased the shear load for the concrete compressive strength of 20 MPa where pryout failure is observed. For the concrete compressive strengths of 30 MPa and 40 MPa, effect of embedment depth is almost negligible were steel failure is observed. At high strain rate of 10^{3} s^{-1}, no influence for the embedment depth on the shear load where steel anchor failure is observed.



(a) Strain rate of 10^{-5} s^{-1} (b) Strain rate of 10^{3} s^{-1}

Figure 7: Effect of embedment depth on the shear load-displacement response of 19.1 mm cast-in-place anchor diameter at low and high strain rates

From Figure 7, it can be seen that at low strain rate of 10^{-5} s^{-1} the increase in the anchor embedment depth from 76.2 mm to 152.4 mm increased the shear load for all the concrete compressive strengths investigated. At high strain rate of 10^{3} s^{-1}, the embedment depth has no effect on the shear load where steel anchor failure is observed.

In general, it can be seen from Figures 4 to 7 that the increase in the anchor diameter from 12.7 mm to 19.1 mm increased the shear load for the cast-in-place anchors. Effect of concrete compressive strength is significant at low strain rate of 10^{-5} s^{-1} where pryout failure is observed while a slight (almost negligible) increase in the shear capacity is observed with the increase in the concrete compressive strength at the high strain rate of 10^{3} s^{-1}. The increase in the shear load is attributed to increase concrete resistance to the shear load with the increase in the concrete compressive strength. Maximum increment in the shear load of 40.8% is obtained for the 19.1 mm diameter cast-in-place anchor at strain rate of 10^{-5} s^{-1} when the concrete compressive strength increased from 20 MPa to 40 MPa where pryout failure mode is observed.

5 CONCLUSIONS

In this paper, finite element analyses using LS-DYNA software package was conducted to investigate the shear behaviour of cast-in-place anchors embedded into concrete at low and high strain rates. The following conclusions can be drawn from the analyses:

- Ultimate shear load at high strain rate of 10^{3} s^{-1} is higher than that at low strain rate of 10^{-5} s^{-1}.
- The ultimate shear load increased with the increase in the concrete compressive strength when failure was by concrete pryout. Maximum increase in the ultimate shear load of 40.8% was obtained for the anchor diameter of 19.1 mm with embedment depth of 76.2 mm when the concrete compressive strength increased from 20 MPa to 40 MPa at low strain rate of 10^{-5} s^{-1}.
- The failure mode of the cast-in-place anchor is influenced by the strain rate. The failure mode of concrete pryout at low strain rates transitions to steel anchor failure at high strain rate.
- More concrete damage was observed for the cast-in-place anchors embedded in lower concrete compressive strength of 20 MPa and shallower embedment compared to that in deeper embedment or higher concrete compressive strengths of 30 MPa and 40 MPa.

References

ACI Committee 318. 2011. *Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary*. American Concrete Institute, Farmington Hills, Michigan, USA.

Alqedra, M.A. and Ashour, A.F. 2005. Prediction of Shear Capacity of Single Anchors Located near a Concrete Edge Using Neural Networks. *Computers & Structures,* **83:** 2495–2502.

Bermejo, M., Goicolea, J.M., Gabald´on, F. and Santos, A. 2011. Impact And Explosive Loads On Concrete Buildings Using Shell And Beam Type Elements. *3rd ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, 1–14.

Bischoff, P.H. and Perry, S.H. 1991. Compressive Behaviour of Concrete at High Strain Rates. *Materials and Structures,* **24**(6): 425–450.

Boh, J.W., Louca, L.A. and Choo, Y.S. 2004. Strain Rate Effects on the Response of Stainless Steel Corrugated Firewalls Subjected to Hydrocarbon Explosions. *Journal of Constructional Steel Research,* **60**(1): 1–29.

British Standards Institution Draft for development. 1992. Concrete - Performane, Production, Placing, and Compliance Criteria. BSI, UK.

British Standards Institution. 2013. Concrete - Specification , Performance , Production and Conformity. BS EN 206, BSI, Uk.

Çalışkan, Ö., Yılmaz, S., Kaplan, H. and Kıraç N. 2013. Shear Strength of Epoxy Anchors Embedded into Low Strength Concrete. *Construction and Building Materials,* **38**: 723–730.

Committee Euro-International du Beton (CEB). 1994. *Fastenings to Concrete and Masonry Structures. State of the Art Report*. Thomas Telford Ltd., London, UK.

Georgin, J.F. and Reynouard, J.M. 2003. Modeling of Structures Subjected to Impact: Concrete Behaviour under High Strain Rate. *Cement and Concrete Composites,* **25**(1): 131–143.

Gross, J.H., Klingner, R.E. and Graves III, H.L. 2001. Dynamic Behavior of Single and Double Near-Edge Anchors Loaded in Shear. *ACI Structural Journal,* **98**(5): 665–676.

Hopperstad, O.S., Børvik, T., Langseth, M, Labibes, K. and Albertini, C. 2003. On the Influence of Stress Triaxiality and Strain Rate on the Behaviour of a Structural Steel. Part I. Experiments. *European Journal of Mechanics, A/Solids* **22**: 1–13.

Jebara, K., Ozbolt, J. and Hofmann, J. 2016. Pryout Failure Capacity of Single Headed Stud Anchors. *Materials and Structures,* **49**: 1775–1792.

Lee, N.H., Park, K.R. and Suh, Y.P. 2011. Shear Behavior of Headed Anchors with Large Diameters and Deep Embedments in Concrete. *Nuclear Engineering and Design,* **241**(3): 608–616.

Livermore software technology Corporation, LSTC. 2012. LS DYNA Keyword User' S Manual VOLUME II Material Models.

Min, F., Yao, Z. and Jiang, T. 2014. Experimental and Numerical Study on Tensile Strength of Concrete under Different Strain Rates. *The Scientific World Journal*, 1–11.

Muratli, H., Klingner R.E. and Graves III, H.L. 2001. Behavior of Shear Anchors in Concrete: Statistical Analysis and Design Recommendations. *International Symposium on Connections between Steel and Concrete*, 220–230.

Murray, Y.D. 2007. Users Manual for LS-DYNA Concrete Material Model 159, 1-77.

Nilforoush, R., Nilsson, M. and Elfgren, L. 2017. Experimental Evaluation of Tensile Behaviour of Single Cast-in-Place Anchor Bolts in Plain and Steel Fibre-Reinforced Normal- and High-Strength Concrete. *Engineering Structures,* **147**: 195–206.

Ross, C.A., Tedesco, J.W. and Kuennen, S.T. 1995. Effects of Strain Rate on Concrete Strength. *ACI Materials Journal*, **92**(1): 37–45.

Sakla, S.S.S. and Ashour, A.F. 2005. Prediction of Tensile Capacity of Single Adhesive Anchors Using Neural Networks. *Computers and Structures,* **83**: 1792–1803.

Ueda, T, Stitmannaithum, B. and Matupayont, S. 1991. Experimental Investigation on Shear Strength of Bolt Anchorage Group. *ACI Structural Journal,* **88**(3): 292–300.

Wu, Y., Crawford, J.E. and Magallanes, J.M. 2012. Performance of LS-DYNA Concrete Constitutive Models. *12 Th International LS-DYNA Users Conference*, 1–13.

Yu, H., Guo, Y. and Lai, X. 2009. Rate-Dependent Behavior and Constitutive Model of DP600 Steel at Strain Rate from 10^{-4} to 10^{3} s^{-1}. *Materials and Design,* **30**: 2501–2505.