Behaviour of expansion bolts connection under axial, Shear and bending interaction

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Abstract: The expansion bolt connection between a steel members and a concrete block is an important point for greater stability of the structure. This expansion bolt joint has to transfer the loads developed by the structure in service. This paper presents the behaviour of expansion bolt connection under axial, shear and bending interaction of base plate connection of cold form steel storage racks. This study motivates to find out the ultimate moment of resistance and stiffness of the base the plate connection for a range of axial loads (i.e., 25%, 50%, 75% and 100%) and compare the experimental results with the analytical modelling using ABAQUS software. The moment rotation characteristics of the connection between the upright and concrete block for a range of axial loads up to the maximum design strength of the upright were studied. In the experimental study, there was no failure observed on the concrete block. The bi-linear moment rotation relationship was adopted for the study and the stiffness of the base plate connection has been found out. A simplified interaction equation was developed for the designer to find the ultimate moment of resistance and stiffness of the base plate connection.

Keywords: Expansion bolts, cold form steel, upright, concrete block, interaction equations.

1. INTRODUCTION: In steel construction, mostly cold-formed steel shapes and hot- rolled steel shapes structural members are used. Hot-rolled steel shapes are moulded at an elevated high temperature while cold-formed steel shapes are moulded at a room temperature. Cold-formed steel members are made of structural sheet steel.

The strength of anchor bolts in grouted concrete masonry were tested monotonically, in direct tension, in direct shear, in combined shear & tension and found that the load deflection behavior of embedded bolts is influenced by bolt diameter, the masonry strength and the level of pre-tightening[1].The authors investigated experimentally the behavior of the steel column base plates subjected to axial loads and moments. Investigators concluded that at the lowest eccentricity, failure was by cracking of the concrete, while at other eccentricities the primary mode of failure was by the yielding of the base plate[2]. The ultimate limit strength of column base connection using limit analysis methods and several failure modes of concrete block, anchor-bolts, plate and column itself are taken into account. It was concluded that the ultimate limit strength curves for pinned and fixed column base connections are in agreement with experimental results[3]. Experimental studies were made on multiple anchor connections loaded monotonically by various combinations of moment and shear and used rigid and flexible base plate with steel attachments connected to concrete[4]. The authors performed extensive research on a calibration of a finite element model for isolated bolted end plate steel connections[5]. Experimental investigations of the application of the component method to column bases were conducted and it was found that any structural joint was considered as a set of individual components and the determination of its mechanical properties such as strength and rotational stiffness[6]. In research on steel storage pallet racks, lateral stiffness in down-aisle direction is usually provided by beam-to-column joints and base-plate connections, owing to the impracticability of using bracing systems in selected areas of pallet racks[7]. The unbolted base plate connection and the development of a numerical model simulate accurately the connection between columns and foundation in metallic structures. In order to validate the results, some experimental models were tested to compare them with the numerical model so that a good agreement and better correlations were obtained between both[8]. The numerical modelling of anchor bolts were tested under pullout and relaxation tests. The anchor rods are pre-stressed in order to minimize the effects of fatigue[9]. The different component affects the rotations of the base plate, which gives a recommendation for the location of the transducers when performing base plate tests to the BS EN 15512:2009 specification[10]. The non-linear model of embedded steel-concrete composite column bases model is constructed and calibrated from the experimental results and is then used for parametric analyses and concluded that the critical zone of the column outside of the block is long and is approximately equal to the height of the steel section[11]. Steel storage racks Figure 1 shows one of the applications of cold-formed steel. Due to their lightness, steel storage racking systems can be raised to a suitable height and can also carry high live load.

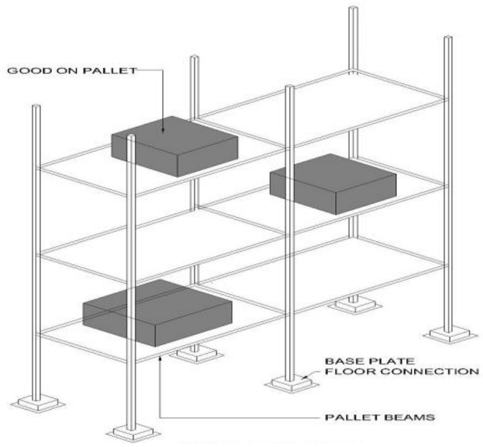


Figure 1. Typical cross section of storage racks.

Base plate connections are usually semi-rigid with a nonlinear moment-rotation characteristic that depends on some factors such as the axial compression of the uprights and the floor anchoring arrangement. The British Standard (BS EN 15512:2009) and the Australian Standard (AS 4084:2012) propose an experimental test method for the determination of the stiffness and moment capacity of base plate connections under static loading. The base plate connections testing arrangement explained in BS EN 15512:2009 was adopted for this research[12].

Based on the previous research, the studies on the behaviour of base plate connections are limited to the base plate thickness 10mm. Hence there is a need to study the behaviour of base plate connections with base plate thickness less than 10mm. In this study the base plate thickness which has been used are 5 mm and 3.15 mm.

The main objectives of this research paper are to investigate the behaviour of base plate connection of cold form steel storage racks; then to find out the ultimate moment of resistance and stiffness of the base plate connection for a range of axial loads (i.e. 25%, 50%, 75% and 100%) and finally, compare the experimental results with the analytical modelling using ABAQUS software.

2. EXPERIMENTAL PROGRAMME

2.1 Compressive Strength calculation using CUFSM (Cornell University Finite Strip Method)

For 90x70x1.6 mm upright model developed using the input menu in the CUFSM software and the boundary condition was applied for the upright.

For upright - 90 mm x 70 mm x 1.6 mm, by adopting the AISI standard the design of cold formed steel structural member are calculated using the direct strength method (Appendix-1, Clause 1.2.1) and the values are tabulated in Table 1.

Table 1. Compressive strength calculation using CUFSM

Type	Dimension of specimens (mm)	Ultimate compressive strength (kN)	Allowable compressive strength (kN)
Type 1	90x70x1.6	90.488	50.271
	90x70x1.8	102.915	57.175
	90x70x2.0	115.608	64.226
Type 2	110x75x1.8	131.387	72.992
	110x75x2.0	150.001	83.334
	110x75x2.5	198.729	110.405
	110x75x3.15	266.27	147.927
Type 3	120x100x2.0	210.635	117.019
	120x100x2.5	279.429	155.238
	120x100x3.15	352.076	195.6

2.2 Compressive strength calculation using British Standard (BS) code

Compressive strength calculations as per the BS, "BS 5950-Part 5 Structural use of Steelwork in Building" are presented in Table 2. The Load applied in the experimental work is based on BS code because ultimate compressive strength calculated using CUFSM software was slightly higher than the BS code.

Table 2. Compressive strength calculation using BS code

Type	Dimension of specimens (mm)	Ultimate compressive strength (kN)	Allowable compressive strength (kN)
Type 1	90x70x1.6	83.848	52.405
	90x70x1.8	94.019	58.762
	90x70x2.0	104.19	65.119
Type 2	110x75x1.8	123.042	76.901
	110x75x2.0	136.336	85.21
	110x75x2.5	169.219	105.762
	110x75x3.15	211.974	132.484
Type 3	120x100x2.0	180.458	112.786
	120x100x2.5	224.688	140.43
	120x100x3.15	281.822	176.139

2.3 Experimental tests setup

The experimental test setup was developed using the British Standard (BS EN 15512:2009). The study of the base plate connection consists of an experimental as well as analytical phase. The experimental setup has 36 tests on 3 different types of upright with corresponding base plates as shown in Table 3.

Table 3. Specimens for experimental study

Type	Specimen	Dimension of specimens (mm)	Size of base plate (mm)
Type 1	A	90x70x1.6	180x110x3.15
Type 1	B	90x70x1.8	180x110x3.15
Type 2	C	110x75x2.0	180x125x5.0

The test arrangement has two equal lengths of cold form upright section and around 4 times the width of the cold form upright section fitted with base plates. The base plates used in this test are standard size and connected to the concrete cube using M12 anchor bolts.

Tests are carried out using M20 grade of concrete. The friction between the concrete cube and the testing apparatus is minimized by steel rollers placed at the bottom of concrete cube to make possible its movement in a horizontal plane, but restrained from rotating about the vertical axis. The upright and base plate connected using M10 grade bolts used shall be the same as that used in practice. The concrete cube shall have parallel faces and shall allow a clearance of at least 50 mm all-round the base plate. Measurement devices shall be fitted to measure the horizontal movement of the concrete cube and the rotation of the column bases relative to the surface of the concrete. The cold form uprights shall be cut normal to their longitudinal axes and the faces of the cube on which the uprights bear shall be parallel so that the axes of both uprights coincide with the line of action of the load.

2.4 Test method

Tests are made over a range of axial load (i.e., 25%, 50%, 75% and 100%). Two hydraulic jacks were used to apply the loads on the cold form upright and concrete cube. Hydraulic jack 1 applies an axial load F_1 on the upright. Hydraulic jack 2 simulates a transverse load F_2 to the center of the cube. After completing the preliminary arrangement, the axial load F_1 is increased (i.e., 25%, 50%, 75% and 100%) and should be made constant during the test. The F_2, transverse load is increased up to the collapse of the specimen. The rotation of the column bases and the horizontal cube displacement are measured with help of dial gauges which is shown in Figure 2. Figure 3 shows the plan view of the experimental setup. The moment applied to the base joint (**M_{bj}**) and the rotation of the base joint (**θ_{bj}**) are calculated using the below mentioned equations and moment rotation curves are plotted, with the help of the moment rotation curve, the ultimate moment of resistance and stiffness were calculated.

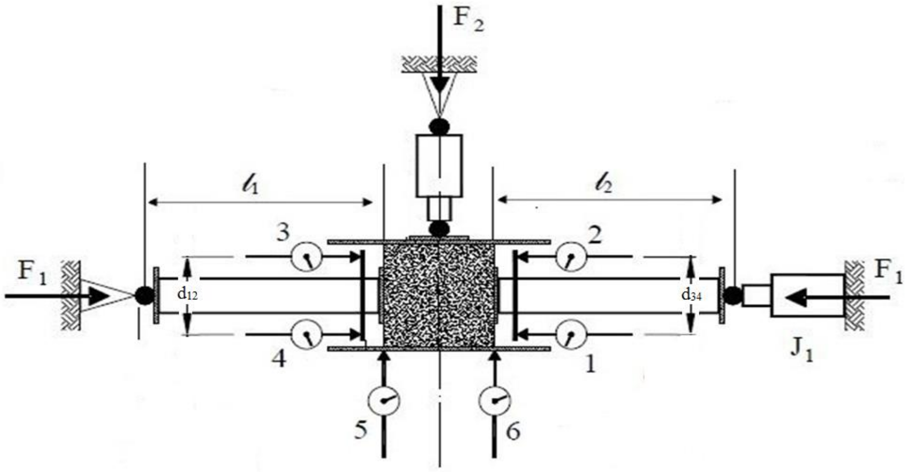


Figure 2. Measurements in test setup.

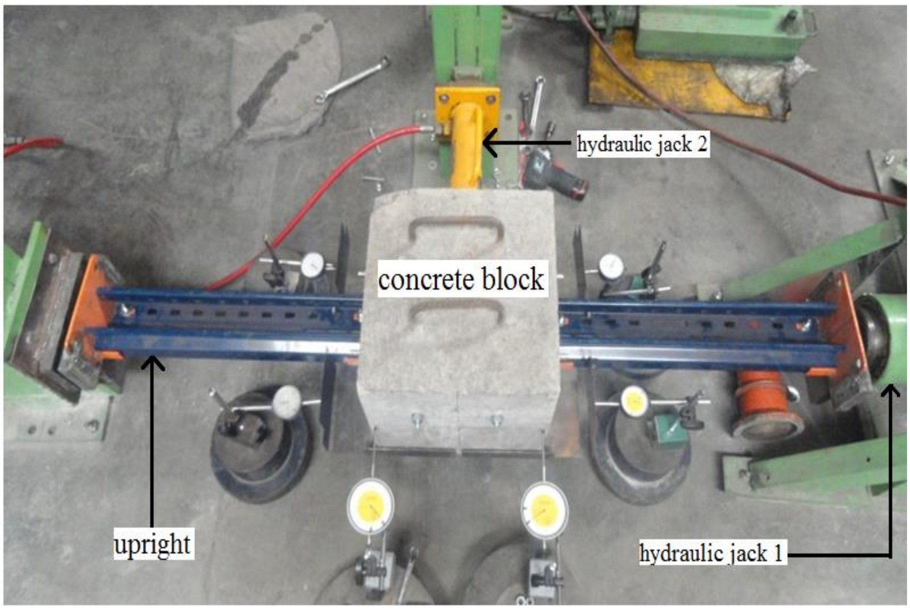


Figure 3. Plan view of the experimental setup.

Moment ($M_{bj)}$ = (F_2 l) /4+ (F_1 $\boldsymbol{\delta}$) (1)

Rotation, $\boldsymbol{\theta_{bj}} = \frac{1}{2}\left[\frac{\delta_3 - \delta_4}{d_{12}} + \frac{\delta_1 - \delta_2}{d_{34}}\right]$ (2)

Where,

$\boldsymbol{\delta}$ = Mean displacement of the concrete cube, l = (l_2+l_1) /2, d_{34} and d_{12} = Distances between dial gauges.

A total of four load cases was chosen with a different compressive load on the upright and the lateral displacement on the concrete cube was measured. The base plate configurations fitted to the upright section were tested over a range of four axial loads from 25% to 100% of the allowable load on the upright. For each type of specimen three tests were carried out. We observed that while increasing axial load, the ultimate moment of resistance, the stiffness of the base plate connection also increased. The results obtained in the different load cases are tabulated in Table 4, which shows the comparison of axial load with an ultimate moment of resistance and stiffness for the three types of specimen.

Table 4. The results obtained at different load cases

Specimen	Axial load (%)	Moment (kN-m)	Stiffness (kN-m/rad)
A	25	0.435	560.993
	50	0.842	725.833
	75	1.062	1082.988
	100	1.013	1191.117
B	25	0.505	313.003
	50	0.742	733.73
	75	1.113	1499.433
	100	1.233	1848.895
C	25	1.124	368.915
	50	1.418	1354.873
	75	1.835	1866.707
	100	2.087	1987.901

3. FINITE ELEMENT MODELLING

Finite element models of the baseplate, concrete block and upright were developed using the ABAQUS software[13]. Base plate behaviour is analyzed by finite element analysis, carried out using the software ABAQUS. The real model developed using the ABAQUS software was the same as that used in the experimental studies. The concrete cube size is 350x350x350 mm and the clearance needed all around the base plate is 50mm. The upright and base plate was modelled on three-dimensional deformable types with the same size used in experimental studies. The boundary conditions adopted are the same as the experimental tests done in the laboratory. At the bottom of the concrete block roller support was provided to move the concrete block in the loading direction X and the remaining displacements and rotations were arrested as shown in Figure 4 , which also shows the meshed view of experimental set up.

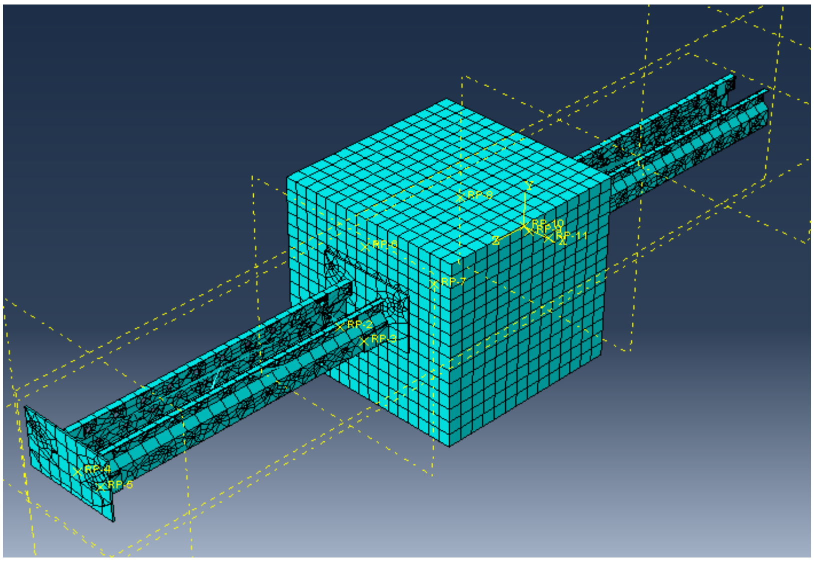


Figure 4. Meshed view.

4. RESULTS AND DISCUSSION

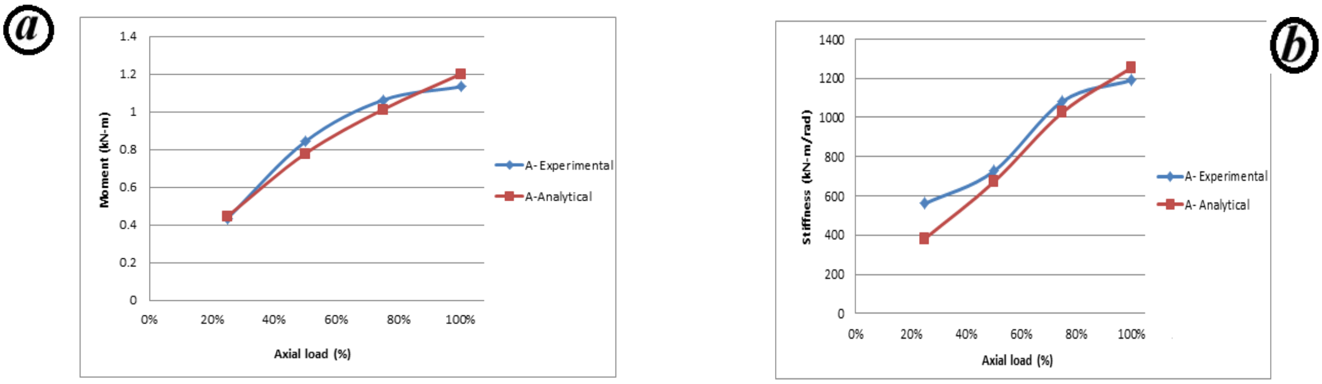
From the analytical test results we observed that while increasing axial load, the ultimate moment of resistance also increased. The results comparison of the axial load with an ultimate moment of resistance and stiffness for the three types of specimen in the different load cases are presented in Table 5.

Table 5. Moment and Stiffness values at different load cases

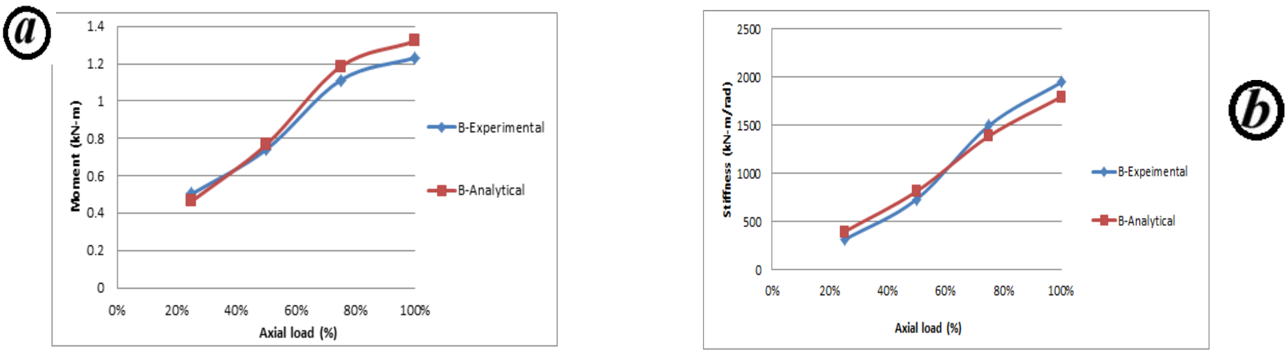
Specimen	Axial load (%)	Moment (kN-m)	Stiffness (kN-m/rad)
A	25	0.446	382.02
	50	0.778	671.00
	75	1.012	1026.91
	100	1.2	1254.35
B	25	0.466	395.99
	50	0.768	816.10
	75	1.185	1390.23
	100	1.321	1796.68
C	25	1.082	430.35
	50	1.354	1347.76
	75	1.718	1788.49
	100	1.951	2021.43

4.1 Comparison of experimental and analytical results

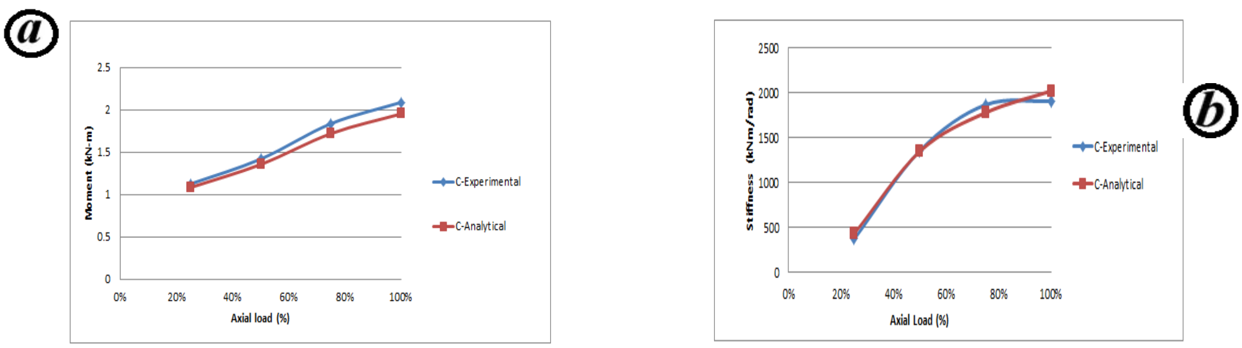
The analytical results were compared with the experimental results obtained in the laboratory. Graphs representing both the analytical and experimental results obtained are drawn in Figure 5 in order to get a good agreement for the estimated ultimate moment and the stiffness.



Specimen A



Specimen B



Specimen C

Figure 5. (a) Ultimate moment curve and (b) Stiffness curve of Specimen A, B and C

From the graph, we could understand while increasing the percentage of axial load the ultimate moment of resistance and the stiffness of the base plate connection increased.

5. INTERACTION EQUATION

Interaction equation developed for the above result using Excel software and the trend line equations is shown in Figure 6 . In the equation, R^2 is a measure of the goodness of fit to the trend line of the data, which is very close to 1. In our curve R^2 value was 0.9599 and in Table 6 the interaction equation for the entire specimen was tabulated

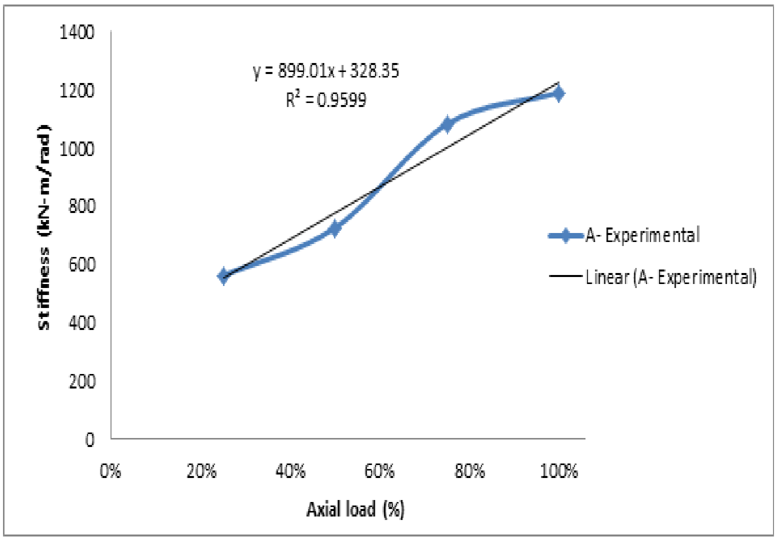


Figure 6. Interaction equation of stiffness curve.

Table 6. Interaction equation for specimens

Specimen	Description	Method	Interaction equation	R^2 value
A	Moment	Experimental	y=0.9256x+0.28895	0.9044
		Analytical	y=0.9984x+0.235	0.9832
	Stiffness	Experimental	y= 899.01x+328.35	0.9599
		Analytical	y=1189.2x+90.339	0.9936
B	Moment	Experimental	y=1.022x+0.2595	0.9679
		Analytical	y=1.1928x+0.1895	0.9679
	Stiffness	Experimental	y=2269.4x - 294.58	0.9865
		Analytical	y=1910.5x+94.302	0.9954
C	Moment	Experimental	y=1.3224x+0.7895	0.9917
		Analytical	y=1.1884x+0.7835	0.9935
	Stiffness	Experimental	y=2051x+92.401	0.885
		Analytical	y=2081.6x+93.511	0.9197

6.CONCLUSION

The experimental setup models have the same structural conditions stipulated in BS EN 15512:2009 and also the same model adopted for finite element modelling. The design strength of the upright was calculated using the CUFSM software and compared with British Standard code. In the experimental study, there was no failure observed on the concrete block. The moment rotation characteristics of the connection between the upright and concrete block for a range of axial loads up to the maximum design strength of the upright were studied. Based on the results of experimental and analytical simulations, the base plate connection of steel storage racks were studied and the following conclusions are drawn.The moment rotation curves were discussed and it was found that while the axial compressive load increases (25%, 50%, 75% and 100%) the ultimate moment resistance value also increases until the test was terminated. The bi-linear moment rotation relationship is adopted for the study and the stiffness of the base plate connection was found out. The results of the static loading were compared and agreed well with available experimental results. Moreover, the estimated bending stiffness values (5–20% deviation) and the magnitude of ultimate moments (about 0-8%) provided by ABAQUS are very similar to those obtained in the laboratory. For the future research instead of doing tedious process like experimental and analytical study, the simplified interaction equations which was developed can be taken to find the ultimate moment of resistance and stiffness of the base plate connection.

References:

[1] Russell Brown, H. and Rhett Whitlock, A., Strength of anchor bolts in grouted concrete masonry. J. Struct. Eng., 1983, **109**, 1362-1374.

[2] David Thambiratnam, P. and Paramasivam, P., Base plates under axial loads and moments. J. Struct. Eng., 1986, **112**, 1166-1181.

[3] Paul Penserini and Andre Colson., Ultimate limit strength of column-base connections. J. Const. Steel Res., 1989, **14**, 301-320.

[4] Cook, R.A. and Klingner, R. E., Ductile multiple- anchor steel -to -concrete connections. J. Struct. Eng., 1992, **118**, 1645-1665.

[5] Bursi, O.S. and Jaspart, J. P., Calibration of a finite element model for isolated bolted end-plate steel connections. J. Const. Steel Res., 1997, **44**, 225-262.

[6] Jaspart, J.P. and Vandegans, D., Application of the component method to column bases. J. Const. Steel Res., 1998, **48**, 89-106.

[7] Baldassino, N. and Bernuzzi, C., Analysis and behavior of steel storage pallet racks. Thin Walled Struct., 2000, **37**, 277-304.

[8] Diaz J. J. D. C., Nieto P. J. G., Biempica C. B., and Rougeot G. F., Nonlinear analysis of unbolted base plates by FEM and experimental validation. Thin Walled Struct., 2006, **44**, 529-541.

[9] Delhomme, F. and Debicki, G., Numerical modelling of anchor bolts under pullout and relaxation tests. J. Constr. Build. Mater., 2010, **24**, 1232-1238.

[10] Gilbert, B. P. and Rasmussena, K., Determination of the base plate stiffness and strength of steel storage racks. J. Constr. Steel Res., 2011, **67**, 1031-1041.

[11] Marisa Pecce and Fernando Rossi., The nonlinear model of embedded steel- concrete composite column bases. J. Eng. Struct., 2013, **46**, 247-263.

[12] AISI Appendix 1., Design of cold formed steel member using the direct strength method, 2007.

BS EN 15512 Steel static storage systems - Adjustable pallet racking systems- Principles of structural design, 2009.

[13] Hibbit Kalsson and Sorensen., ABAQUS user's manual, United states of America, 2011.

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