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Experimental and Analytical Study on Failure Modes of Structural Steel Scaffolds

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Abstract

Steel scaffolds are temporary structures usually used in construction to support various types of loads. Four 3D full-scale scaffold-frames with different geometric and connection properties were constructed and tested statically in Cairo University Structures Lab. The aim was to obtain the strength as well as the failure modes of these four common scaffolds available in the local construction market. Nonlinear Finite-Element-Analysis was conducted for the four frames in order to verify strength and failure modes of the scaffolds and to compare with experimental results. Parametric studies were carried out based on the Finite-Element-Analysis results, in order to investigate the influence of various geometric arrangements and properties on the behavior of similar scaffolds. Based on both experimental and analytical results, it was concluded that the most common failure mode for 3-D free-standing-scaffolds was the sway-frame-buckling about its weak plane. For quick-form scaffolds (e.g. Cuplock and wedge types), the failure load-factor was found to be very sensitive to the rotational stiffness of the "standard-to-ledger" connection. For X-braced-scaffolds, the failure load-factor was shown to depend on the tie height. Other conclusions and recommendations are presented to the construction industry.

1. Introduction

For many years, steel scaffolding has been commonly used during construction due to its ease of fabrication, installation and dismantling. Scaffolds are usually used to support workers and construction materials. They are used for two main purposes: 1) finishing the building facades (access scaffolds to provide a safe working space); and 2) as a shoring system to support construction loads and fresh concrete until it hardens (support scaffolds). The vertical loads on scaffolds can be from laborers, construction equipment, formworks and construction materials. Scaffolds must also be designed to withstand lateral loads, including wind, impact, and earthquake loads.

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Access scaffolding is erected in a single row where cross-braces only exist on one side and works are usually processed at the edge closest to the building when workers perform operations such as installing the vertical formwork and plastering the facades.

Support scaffolding is erected in multiple rows and cross-braces exist on both sides. They are sometimes called false work and are subjected to heavy loads such as fresh concrete weight.

2. Previous Work

Many recent studies on scaffold behavior were carried out through three-dimensional models and compared to full scale test results such as those presented by Chandrangsu and Rasmussen [2011], Prabhakaran et al. [2006] , Milojkovic et al. [2002] , and Godley and Beale [1997]. Chandrangsu and Rasmussen [2008] made a simplification to optimize the Cuplock semirigid connection with a tri-linear moment rotation curve that depends on the setup of the Cuplock joint, Figure 1.

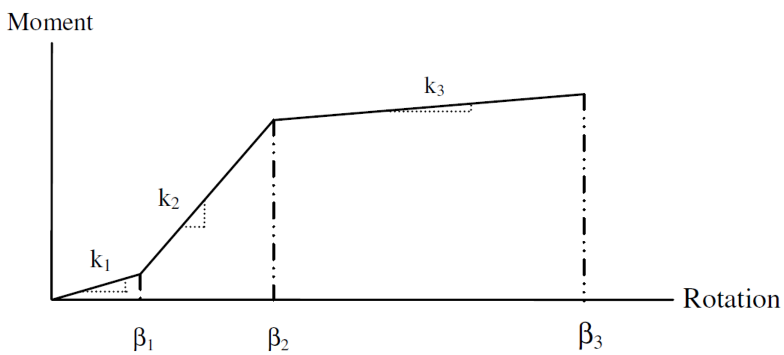


Figure 1: Tri-linear moment-rotation curve for Cuplock joints
(Chandrangsu and Rasmussen [2008])

3. Full-Scale Subassembly Tests

3.1 Test Setup and Procedures

A total of four different scaffold systems (Cuplock - Wedge type - Braced frame - Braced frame with tie) were tested in Cairo University Structures Lab to study their behavior and assess their ultimate load-carrying capacities, Figure 3.

All tested components were taken from stocks of used materials. As a result, most members showed geometric imperfections commonly encountered in practice, particularly the out-of-straightness of the standards. Besides, the Cuplock and Wedge joints showed signs of wear from frequent use and were therefore representative of joints used in practice in terms of joint stiffness and strength.

Figure 2: Tested scaffolds: Cuplock - Wedge type - Braced frame - Braced frame with tie

A special loading steel frame 6 m high was fabricated for full scale tests. A 500 KN hydraulic jack was fastened to the top of the loading frame, and applied vertical load to the top steel distribution beam. The load was transferred to two bottom steel distribution beams in the perpendicular direction, and finally to the scaffold columns as four concentrated vertical loads, as shown in Figure 3.

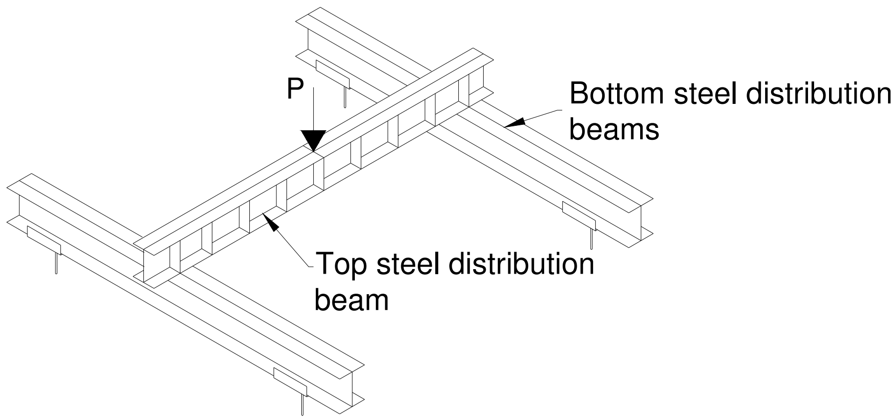
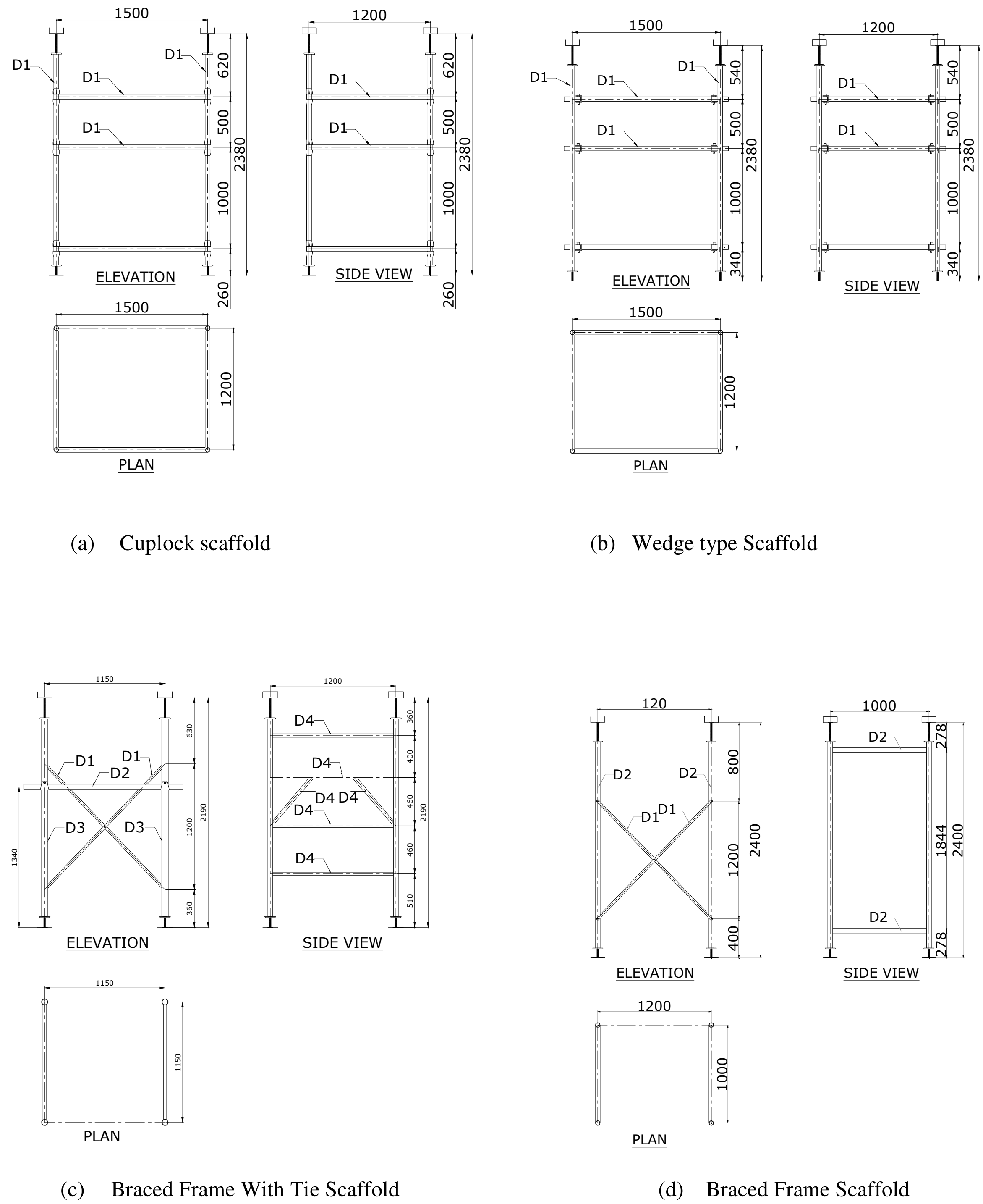


Figure 3**:** Load distribution beams

3.2 Test Configuration

The steel tubes used in the test specimens had a diameter of 48 mm and a thickness of 3 mm for the semi-rigid scaffolds (Cuplock - Wedge type). The diameters of the Braced Frame with tie steel tubes are listed in Table 1 . The scaffold was assembled by experienced workers the same as in site. Displacement measures were recorded during test till failure at two points, point 1 at the top U-head of the scaffold (Horizontal and Vertical displacement were measured) and point 2 at 80 cm from the bottom (Horizontal displacement was measured). The frame out-of-plumb (Δ) was measured at the U-head at top of scaffold and at each standard to ledger connection it was found to be almost linear so it was considered in the ANSYS model.

Loading of the hydraulic jack was applied manually till the scaffold tends to fail due to large displacement. Considering the safety of the experiments, collapse of the specimens was not allowed. Since the pressure in the hydraulic jacks will decrease once the scaffold specimen reach the peak load and start unloading due to instability, the specimens would be considered “failed” at this point and the test will be stopped.



(a) Cuplock scaffold

(b) Wedge type Scaffold

(c) Braced Frame With Tie Scaffold

(d) Braced Frame Scaffold

Figure 4**:** Configurations of scaffold tests

Table 1: Cross-sections of used pipes

Section	D (mm)	t (mm)
D1	25.4	2
D2	48	2.5
D3	60	3.5
D4	32	2

3.3 Test Results

A summary of the test results is shown in Table 2, Failure load from hydraulic jacks and observed failure mode are shown. As noted earlier, the results of the Braced frame scaffold was unrepresentative, and thus not shown in the summary.

Table 2 : Results Summary (1 ton = 10 KN)

Scaffold	Failure load (tons)		Failure Mode	Frame out-of-plumpness (mm)		Final Displacement (mm)	
	Test	FEM		Δ_{xi}	Δ_{yi}	Δ_x	Δ_y
Cuplock Scaffold	27.8	27.19	Global Buckling	24	16	20	N/A
Wedge type scaffold	26.1	25.39	Global Buckling	20	15	20	23.1
Braced Frame with Tie	39.8	38.9	Yielding of standards	0	0	8.1	5.35

The test results show the tri-linear behavior of the semi rigid scaffolds and the massive effect of the frame out of plumpness on the overall strength of the steel scaffolds.

Also the dynamic loading of the hydraulic jack noticed to make strong vibrations in the beginning of loading, the frame stiffened after a while till it became loose again when it was about to fail.

Figure 6: Yielding of Standards in Braced Frame with tie Scaffold.

4. Finite Element Modeling

The three-dimensional finite element models developed for analyzing support scaffold systems include geometric and material nonlinearities are performed using the commercial finite element software package ANSYS. The models present efficient and accurate methods for representing standard-to-ledger connections and load eccentricities. Also, the initial geometric imperfections and material nonlinearity of all components of the system are incorporated in the models. In modeling the structural elements of the support scaffold system, nonlinear beam and connection elements are used. The models are compared with the subassembly tests and calibrated against the ultimate loads and displacement responses.

The challenge in modeling of Cuplock scaffold and Wedge type was to accurately simulate the semi rigid connections. It was found that we can use a constant rotational stiffness ($k_{\theta x}$ and $k_{\theta y}$ $=0.9\ k_{\theta}$) for the Cuplock connection and ($k_{\theta x}$ and $k_{\theta y} = 0.78\ k_{\theta}$) for the wedge type connection. Where k_{θ} is the rigid bending-stiffness of the standard-to-ledger connection. This constant rotational stiffness gives a fairly accurate ultimate load for the frame; but does not predict the load-deformation behavior very well due to the high connection-sensitivity to its initial setup as shown in Figure 1.

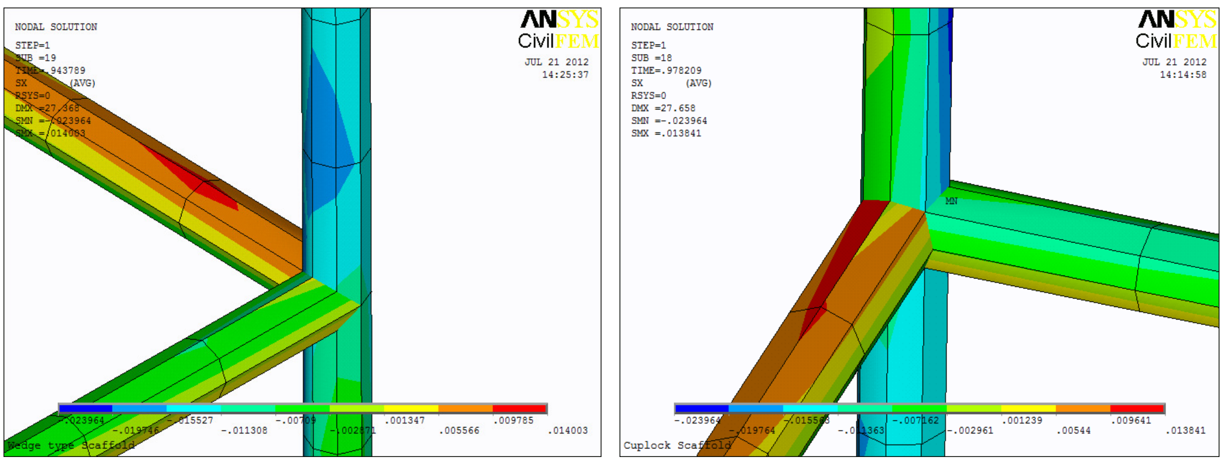


Figure 7: Normal stress at ledgers to standards connections (Cuplock-Wedge type)

Modeling of braced frame scaffold was much easier than the previous models as bracing joints were identified as couple nodes, the rest of the joints were considered as fixed connections even the tie. We can get results that are close enough to the final load obtained from experimental work and displacements of frame at the same points (1 & 2).

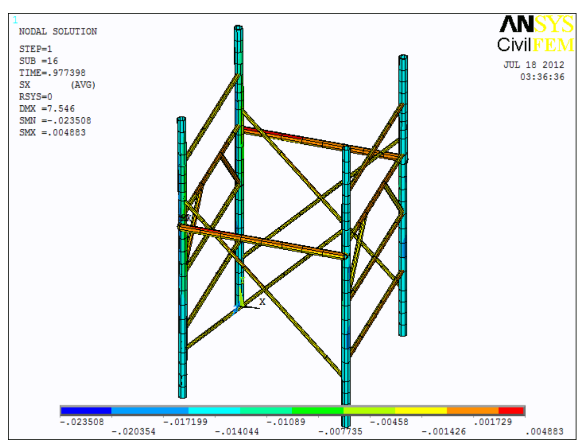
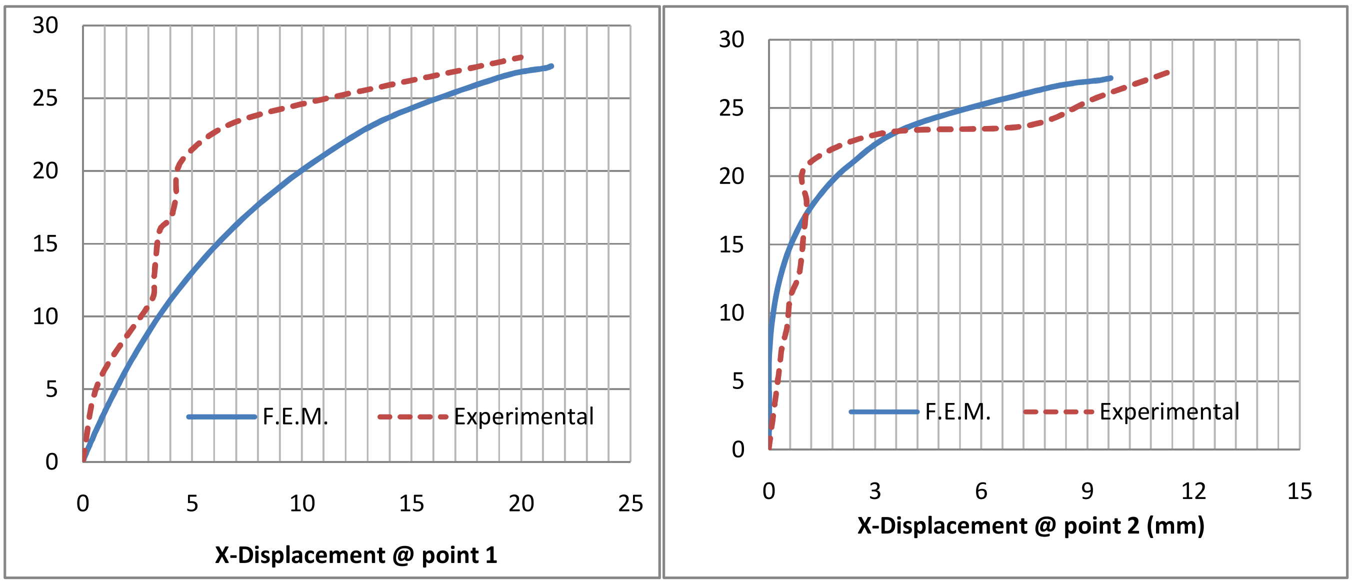


Figure 8: Normal stress of Braced Frame with Tie

The model includes the geometrical imperfections and the material nonlinearities.

It is clear that the bottom end of the scaffold system was not restrained in the horizontal direction, and theoretically it is free. However, no horizontal displacements were ever observed at this location during the tests as well as in common practice, therefore the boundary condition here could be considered as hinges.

It was noticed that the Cuplock and Wedge type scaffolds failure was due to Global buckling in X direction. Maximum stress occurs at Standard to Ledgers connections Figure 7.



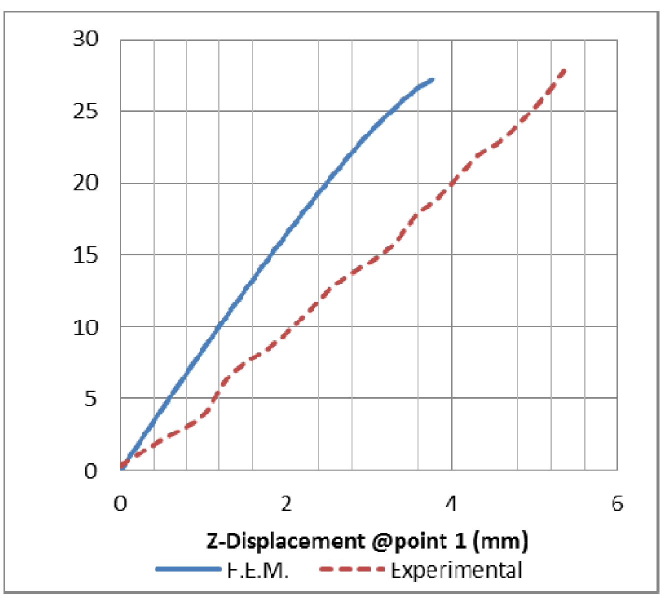


Figure 9**:** Load (in tons) vs. displacement curves of Cuplock Scaffold (1 ton = 10 KN)

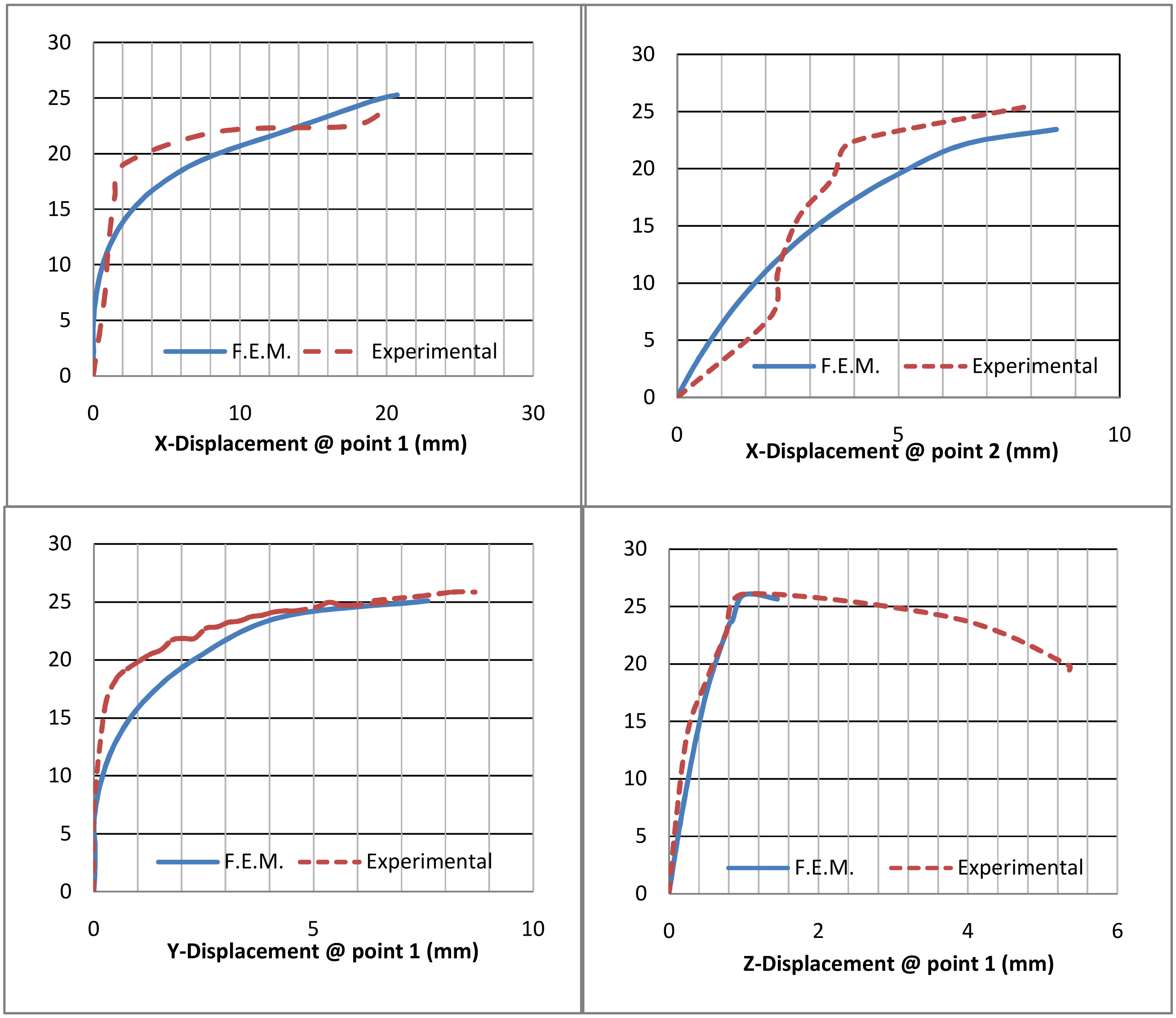


Figure 10: Load (in tons) displacement curves of Wedge type Scaffold
(1 ton = 10 KN)

5. Tie Location and Ledger Removal Effects

Parametric studies were conducted on the scaffold model, in order to identify the dominant factors for the strength of scaffolds. Parameters investigated included the tie height in the Braced frame scaffold and the removal of one of the ledgers in the Cuplock system. The failure load-factor was shown to depend on the tie location and placing it must be in adequate height from the base to reduce unsupported length and maintain the maximum efficiency of the scaffold. A summary of the tie height effect is listed in Table 3.

Effect of removal of one of the ledgers on the load factor is shown in Tabel 4.

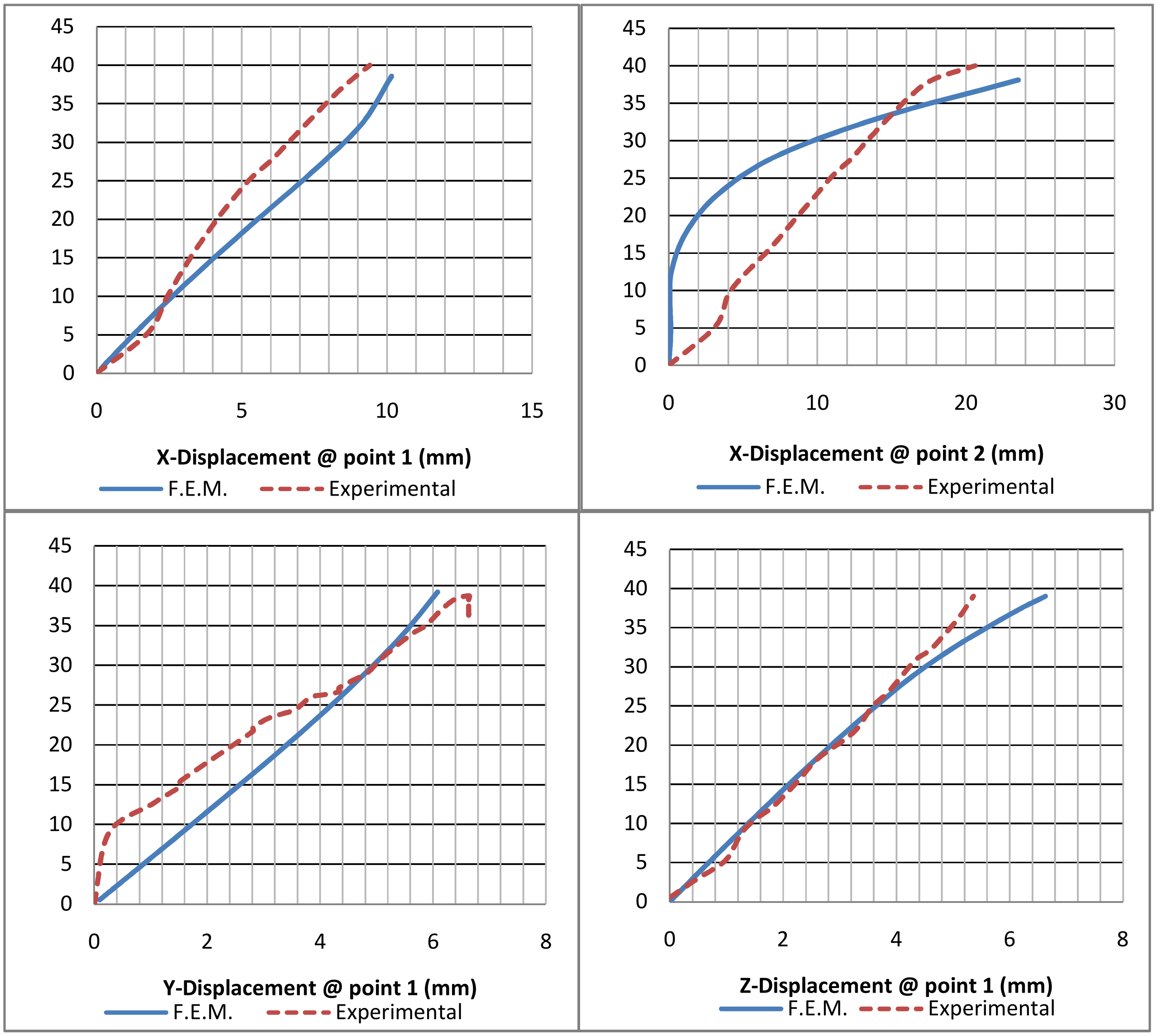


Figure 11: Load (in tons) displacement curves of Braced frame with tie Scaffold
(1 ton = 10 KN)

Table 3: Failure load vs. tie location

Tie location (H)	without tie	H = 1.34 m	H = 1.14 m	H = 0.84 m	H = 0.34 m
Failure Load (ton)	35.6	38.9	42.2	40.4	43.7
Failure Load Ratio	0.91	1.00	1.08	1.04	1.12

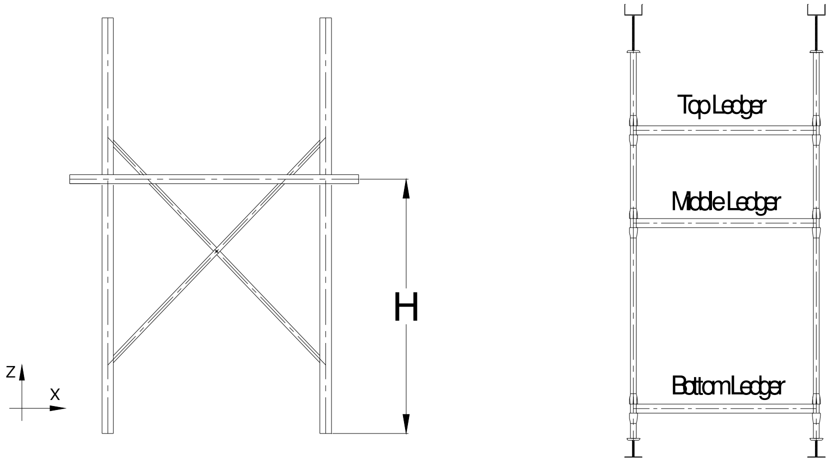


Table 4: Effect of Ledgers Removal in Full Cuplock Scaffold

Removed Ledger	Middle	Top	bottom
Failure Load ratio	0.67	0.47	0.35

6. Conclusions

A comprehensive study was conducted on the stability and strength of scaffolds through four full-scale tests as well as dozens of FEM analyses. Simplified models were developed for the scaffolds posts and procedures were proposed for an efficient and effective design. The following conclusions were made:

1. For quick-form scaffolds (e.g. Cuplock and Wedge types), the failure load-factor was found to be sensitive to the rotational stiffness of the “standard-to-ledger” connection and the storey height.
2. Semirigid connections of the Cuplock and Wedge type scaffolds can be considered to have constant rotational stiffness about major axes in analytical models to get the failure load and final displacement but not the full load-displacement behavior.
3. The most common failure mode for 3-D free-standing-scaffolds is the sway-frame-buckling about its weak plane.
4. For X-braced-scaffolds, the failure load-factor was shown to depend on the tie height.
5. The bottom end of the scaffold system was not restrained in the horizontal direction, and theoretically it is free. However, no horizontal displacements were ever observed at this location during the tests as well as in common practice, therefore the boundary condition here could be considered as hinges.

6. The failure of the scaffolds is highly influenced by initial geometrical imperfections, therefore, these imperfections should be considered in design models as initial displacements or additional lateral load.
7. Scaffold design must be done very carefully to determine the suitable location of its versatile elements such as ledgers and tie locations.

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