EXPERIMENTAL EVALUATION OF TIE BAR EFFECTS ON STRUCTURAL BEHAVIOR OF SUSPENDED SCAFFOLDING SYSTEMS

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ABSTRACT: The collapse of scaffolds can bring about substantial damage and economic loss. In recent years, over hundreds of people died and an even greater number have been injured because of inadequate scaffolding system designs. In this study, the effects of truss height and number of tie bars on the structural behavior of suspended scaffolding systems were experimentally investigated. Three full-scale scaffolding systems with truss heights of 30, 45, and 60 cm were tested in the laboratory. Each system included a wooden floor, steel purlins and trusses. The number of steel tie bars connected to the systems was also varied. A load transmission system was placed in these experimental systems to distribute single loads to the center of a specific area in a step-by-step manner using a load jack. After each load increment, the displacement was measured by means of linear variable differential transducers placed at critical points of the wooden floor, purlins, and trusses. This test was repeated for all systems and under all system conditions. The test results revealed that displacement increased exponentially in scaffolds with truss heights of 30, 45, and 60 cm without tie bars. Under the same load, systems with truss heights of 60, 45, and 30 cm revealed displacements of 8.8, 12.1, and 23.3 cm, respectively. The results of this work demonstrate that the number of tie bars and truss height considerably affect the structural behavior of scaffolding systems. Our findings further suggest that a scaffolding system with 60 cm-high truss and two tie bars presents optimal safety and cost-savings.

Keywords: Laboratory model, Load-displacement curve, Load transmission platform, Suspended scaffolding system, Tie bar effects, Truss height

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1. INTRODUCTION

Recent developments in technology have allowed possible the construction of various structural systems such as bridges, dams, tunnels, and multi-story buildings. To complete the construction of these systems, workers, building materials, work instruments, and other devices must be carried from the ground to higher levels. Scaffolding systems are temporary structures erected around a construction site to provide a safe working environment to workers and carry tools upward from the ground level. Several scaffolding types have been developed according to a number of site requirements. The most common scaffolds include supported platform systems, adjustable scaffolding systems, and suspended scaffolding systems. Supported scaffolding systems are made of wood and metal structures supported by poles and frames fixed to ground. Adjustable scaffolding systems are raised and lowered using pulleys. Suspended scaffolding systems are platforms suspended from the top of a building using ropes (Url-1). When choosing a scaffolding type, several factors such as the condition of the ground over which the scaffold will be erected and the project design, budget, and schedule must be considered. For example, if the ground around the construction site is unstable or if the scaffold to be erected will prohibit access to other parts of the structure being built, a suspended scaffolding system may be best. A suspended scaffold is relatively safer than a platform that is dozens of stories high (Figure 1 (Url-1a-g [1]). A supported platform scaffold can provide excellent flexibility for tall buildings, Url-2 [2]).


a) b) c) d) e) f) g)

Figure 1. Practical Uses of Suspended Scaffolding Systems (Url-1a-g [1])

Scaffolding systems are mainly made of wood and metal. The wood is obtained from trees such as pine, poplar, and willow, and the metal elements usually include aluminum, galvanized steel, and composite materials. The metal components of scaffolds are generally formed as frames or tubes. These elements are manufactured according to the desired length and connected or tied to each other to construct to scaffold. Scaffolds also require couplers and planks; the couplers connect the elements and the planks make up the working platform. These planks can be made of wood or metal (Url-3 [3]).

Damage to property, personal injury, and death may result from poorly designed scaffolds or non-observance of routine precautions. For example, according to a report by the United States Bureau of Labor Statistics, in 2007, 88 fatalities occurred from scaffolds. A recent study found that 72% of the injuries suffered in scaffold accidents could be traced back to the support giving way or the worker slipping through the scaffold frame or being struck by a falling object. In the United Kingdom, about 50 people die each year because of scaffold collapse and over 4,500 workers have been injured by faulty or defective scaffolds. (Collins et al. [4]; Url-4 [5]). Thus, the structural safety of scaffolding systems must be investigated and precautions must be taken during the construction and operation of these systems.

The importance of scaffold safety was highlighted in previous studies, such as those of Peng et al. [6-7]. In their first study, these authors focused on the development of a computer model based on actual construction practices to provide a description of the likely causes of scaffold support system collapse during construction. An examination of the effect of the combination of wooden shores with modular steel scaffolds on the performance of temporary support structures then followed. In their second study, the authors presented a simplified structural analysis procedure for high-clearance scaffolding systems based on a “set” concept. The validity of this simplified procedure was then confirmed by comparing results with the more refined computer model developed in their first study. Figure 2 shows the aftermath of the collapse of suspended scaffolding systems (Url-5a-g [8]).

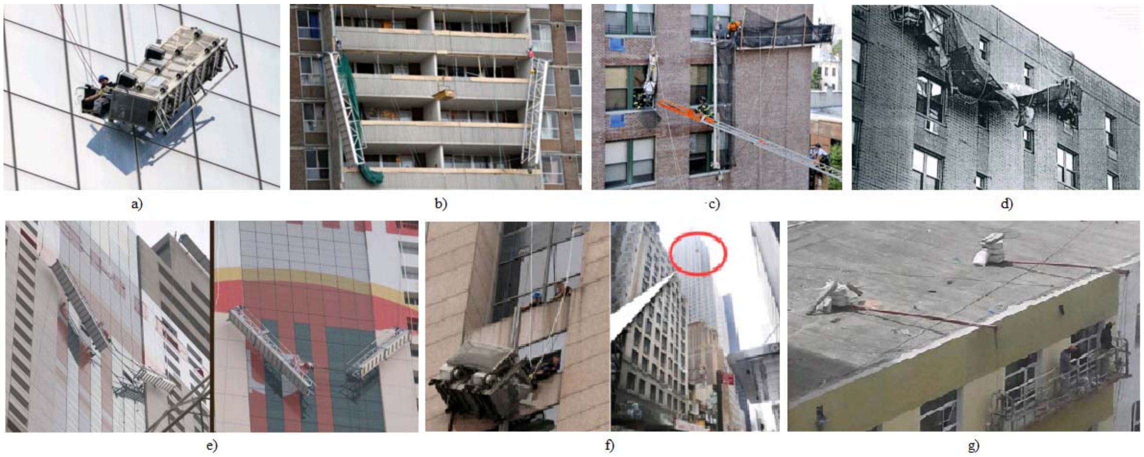


Figure 2. Collapse of Suspended Scaffolding Systems (Url-5a-g [8])

Recent years have shown an increase in research on scaffolding safety (Khudeira [9]; Pishes et al. [10]). Hill et al. [11]) studied the design of suspended-scaffold structural support elements and lifeline anchorages according to federal OSHA requirements. Chuyang and Luli [12] researched the finite element model of a scaffolding system to determine the influence of joint stiffness on the overall stiffness of the scaffold and load distribution at the bottom of bowl scaffolds. Romera et al. [13] observed that many construction accidents are caused by deficiencies in the project design phase. Beale [14] published a review of scaffolding and falsework structures performed over the last 40 years; this review also discussed the finite element modeling and testing procedures of scaffolds and provided recommendations for modeling connections and different loads on scaffolding systems. Kim and Teizer [15] developed a rule-based system that could automatically plan scaffolding systems for pro-active management in building information modeling.

Studies related to the analysis and design of scaffolding systems have been performed by many researchers. Peng et al. [16] analyzed the structures and models of scaffolding systems used in construction. Prabhakaran [17] performed nonlinear analysis of scaffolds with semi-rigid connections. Son and Park [18] investigated the structural behavior of steel-pipe scaffoldings based on the tightening strength of clamps using MIDAS structural analysis software. Chandrangsu [19] performed an advanced analysis and probabilistic-based design of support scaffolding systems. Chandrangsu and Rasmussen [20] developed three-dimensional advanced analysis models to determine the behavior of support scaffolding systems; this study also described the methods for modeling spigot joints, semi-rigid upright-to-beam connections, and base-plate eccentricities. Prabhakaran et al. [21] developed an algorithm to model scaffold behavior and study the full moment-rotation curve including nonlinear loading and unloading behavior; here, different approximations of the moment–rotation curves were presented and applied to simple frames. Yue and Yuan [22] developed design methods of integral-lift tubular steel scaffolds for high-rise building construction; in this study, dead loads, live construction loads, and wind loads for integral-lift scaffolds were presented. Zhang and Rasmussen [23] investigated the behavior of steel scaffold structures using advanced analytical tools by considering system-based designs. Experimental studies have also been performed by several researchers (Chandrangsu and Rasmussen [24]; Liu et al. [25]; Peng et al. [26]; Andre et al. [27]; Peng et al. [28].

Considering the importance of scaffold safety and the lack of literature to describe it, more experimental studies must be done to investigate the structural behavior of scaffolding systems to decrease the risk of accidents caused by design deficiencies. The present study evaluates the structural behavior of scaffolding systems subjected to several loading tests. First, the general requirements to design and construct scaffoldings are provided. Then, the test procedure and scaffolding systems constructed in the laboratory are described. Afterward, loading tests are performed on suspended scaffolding systems with different numbers of tie bars at three different truss heights, and the results of these tests are reported. Finally, this paper summarizes the considerable effects of number of tie bars and truss height on the structural behavior of scaffolding systems.

2. GENERAL REQUIREMENTS FOR SUSPENDED SCAFFOLDING SYSTEMS

The United States Occupational Safety and Health Administration (OSHA3150 [29]) has provided general requirements and guidelines for constructing suspended scaffolding systems. According to OSHA3150, each suspended scaffold and scaffold component must support its own weight and at least four times the maximum intended load applied or transmitted to it without failure. Also, scaffolds and scaffold components must not be loaded in excess of their maximum intended load or rated capacity, whichever is less. Load-carrying timber members should be a minimum of 10.34 kN/m^2 construction-grade lumber, and, during construction, each platform must be planked and decked as completely as possible with a space between the platform and uprights of not more than 2.5 cm wide. This space must not exceed 24.1 cm when side brackets or odd-shaped structures result in a wider opening between the platform and the uprights, and the platform deck must not deflect by more than 1/60 of the span when loaded.

Suspended scaffolding systems contain one or more platforms suspended by ropes or other non-rigid means from an overhead structure; some examples of these scaffolds include the single-point, multipoint, multi-level, and two-point adjustable scaffolds. In these systems, all of the support devices must rest on surfaces capable of supporting at least four times the load imposed on them. When scaffold platforms are more than 61 cm above or below a point of access, ladders, ramps, walkways, or similar surfaces must be used. When lanyards are connected to horizontal lifelines or structural members on single-point or two-point adjustable scaffolds, the scaffold must have additional independent support lines equal in number and strength to the suspension lines, and these support lines must have automatic locking devices. Counterweights used to balance adjustable suspension scaffolds must be able to resist at least four times the tipping moment imposed by the scaffold operating at either the rated load of the hoist or one and a half (minimum) times the tipping moment imposed by the scaffold operating at the stall load of the hoist, whichever is greater. A single tieback must be installed perpendicular to the face of the building or structure. Two tiebacks installed at opposing angles are required when a perpendicular tieback cannot be installed. The suspension ropes must be long enough to allow the scaffold to be lowered to the level below without the rope passing through the hoist, and the end of the rope must be configured to prevent the end from passing through the hoist. Suspension ropes supporting adjustable suspension scaffolds must be of a diameter large enough to provide a surface area sufficient for installing brake and hoist mechanisms (OSHA3150 [29]).

3. EXPERIMENTAL TESTS OF THE SUSPENDED SCAFFOLDING SYSTEMS

3.1 Description of the Scaffolding Systems

The effects of different tie bar numbers on the structural behavior of suspended scaffolding systems were experimentally determined. Three full-scale 3D steel pipe-rack suspended scaffolding systems with different truss heights were constructed in our laboratory for this test. Each scaffold was built with two plane trusses impended on two plane frame systems (Figure 3). The height of the trusses of the first, second, and third scaffold was 30, 45, and 60 cm, respectively. These systems were named

T30, T45, and T60, respectively. The plane trusses of all three scaffolds were connected with purlins over which a wooden board was placed. The frame systems of these scaffold were not fixed to the soil, but the beam and column elements of these frames featured rigid connections. The purlins were connected to the plane trusses via pins; trusses were also connected to the frame system via pins. The connections of the system were provided by 48/48 swivel couplers and girder gravlock clamps. The wooden boards were placed on the purlins without fixing. The span width and length of the scaffoldings were 1.6 and 6 m, respectively, and the outer diameter and pipe thickness of the trusses were 48.3 and 3.2 mm, respectively.

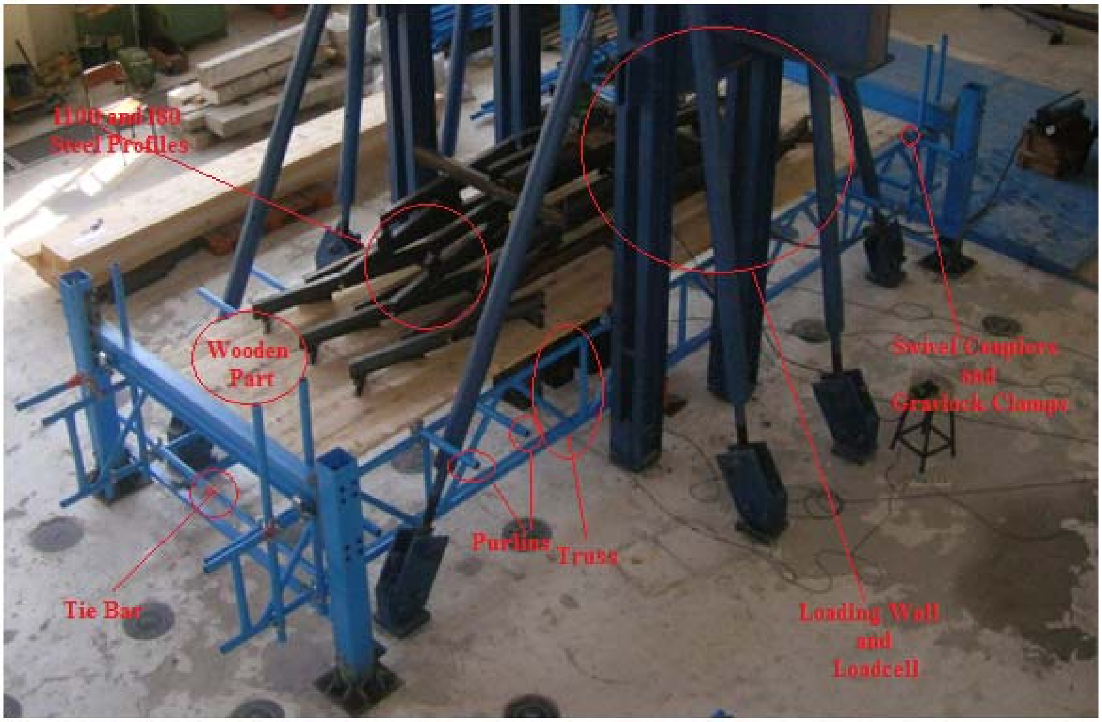


Figure 3. Full-scale 3D Steel Pipe-rack Suspended Scaffolding System

In this study, scaffolds with different system connections were subjected to five loading tests to determine their structural performance. In the tests, a single load from a vertical hydraulic jack with 100 kN capacity was applied to the wooden floor (6 m × 1.6 m) of the scaffolds. A platform was developed to transmit single loads to the specified area. The load transmission platform was constructed with five levels using I100 and I80 steel profiles, which were selected according to the loads to be applied, the transmission distances, and rigidity of the systems. In the tests, the single load via transmission platform is distributed to scaffolding wooden floor, then the loads are carried by purlins and is transmitted to plane trusses, lastly the loads are taken from plane frames (See Figure 4).

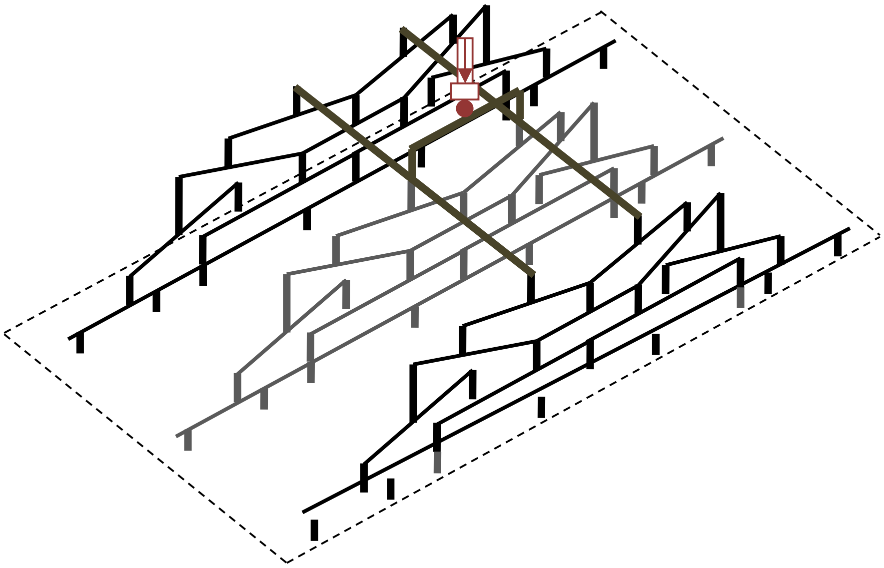


Figure 4. Schematic View of the Developed Load Transmission Platform

3.2 Experimental Tests

The loading tests were performed under five system conditions to evaluate the effects of the number of tie bars on the structural performance of the suspended scaffolds. The means of system conditions is the numbers of the tie bars, which are used to connect the plane trusses at the bottom level (Figure 5). Figure 5 also illustrates the plane trusses and purlins of the scaffolding systems. The systems are prefixed T to reflect the height of the truss, and the system conditions are identified as numbers of tie bars. The names of the scaffolds are provided below:

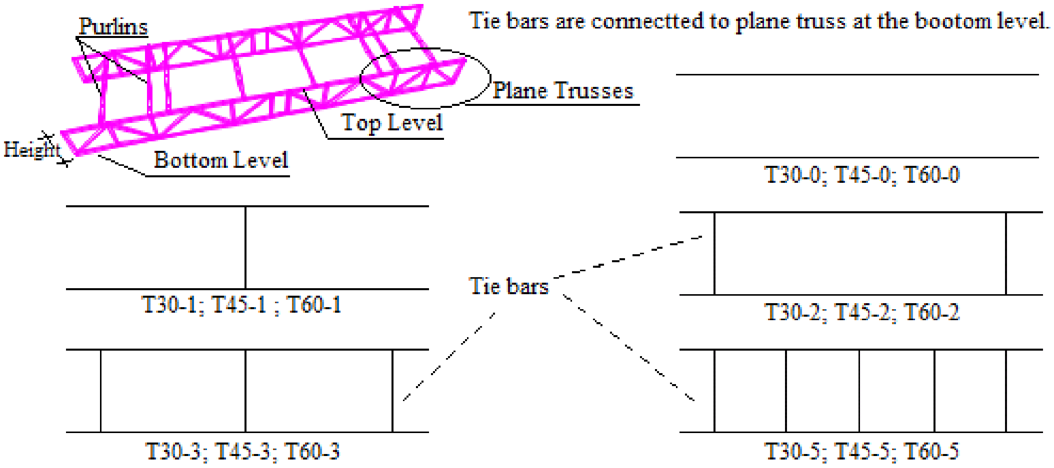


Figure 5. Truss Systems and System Conditions of the Scaffolds Used in the Loading Tests

System names:

- **T30:** The height of the truss is 30 cm
- **T45**: The height of the truss is 45 cm
- **T60:** The height of the truss is 60 cm

System conditions:

- **T30-0:** No tie bar in the system
- **T30-1:** One tie bar at the middle of the plane truss
- **T30-2:** Two tie bars at the beginning and end of the plane truss
- **T30-3:** Three tie bars at the beginning, middle, and end of the plane truss
- **T30-5:** Five tie bars placed at equal distances from the beginning to end of the plane truss
- **T45-0:** No tie bar in the system
- **T45-1:** One tie bar at the middle of the plane truss
- **T45-2:** Two tie bars at the beginning and end of the plane truss
- **T45-3:** Three tie bars at the beginning, middle, and end of the plane truss
- **T45-5:** Five tie bars placed at equal distances from the beginning to end of the plane truss
- **T60-0:** No tie bar in the system
- **T60-1:** One tie bar at the middle of the plane truss
- **T60-2:** Two tie bars at the beginning and end of the plane truss
- **T60-3:** Three tie bars at the beginning, middle, and end of the plane truss
- **T60-5:** Five tie bars placed at equal distances from the beginning to end of the plane truss

A vertical hydraulic jack placed loads at the center of the transmission platform of each system described above. After each test, the system was unloaded, the system was brought into the startup, and the tie bars were reconnected to achieve other system conditions. While excess loads were not applied to the scaffolds, the structures were loaded by as much as their steel profiles and connection rigidities would allow. The load–displacement curves of each test were determined from five critical points of the scaffolding systems using linear variable differential transducers (LVDTs) (Figure 6). The first critical point was the midspan of the scaffold; the LVDT for this point was placed on the wooden floor. The second and third critical points were at the midspans of the purlins, and the fourth and fifth critical points were the midspans of the plane trusses. Photographs taken during the loading tests are shown in Figure 7. While the systems were not loaded until collapse, several scaffolds demonstrated some degree of deformation under certain loads. Figure 8 shows the deformations of T30-0, T45-0, and T60-0.

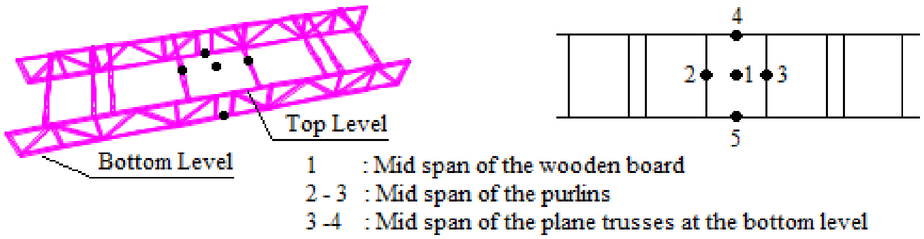
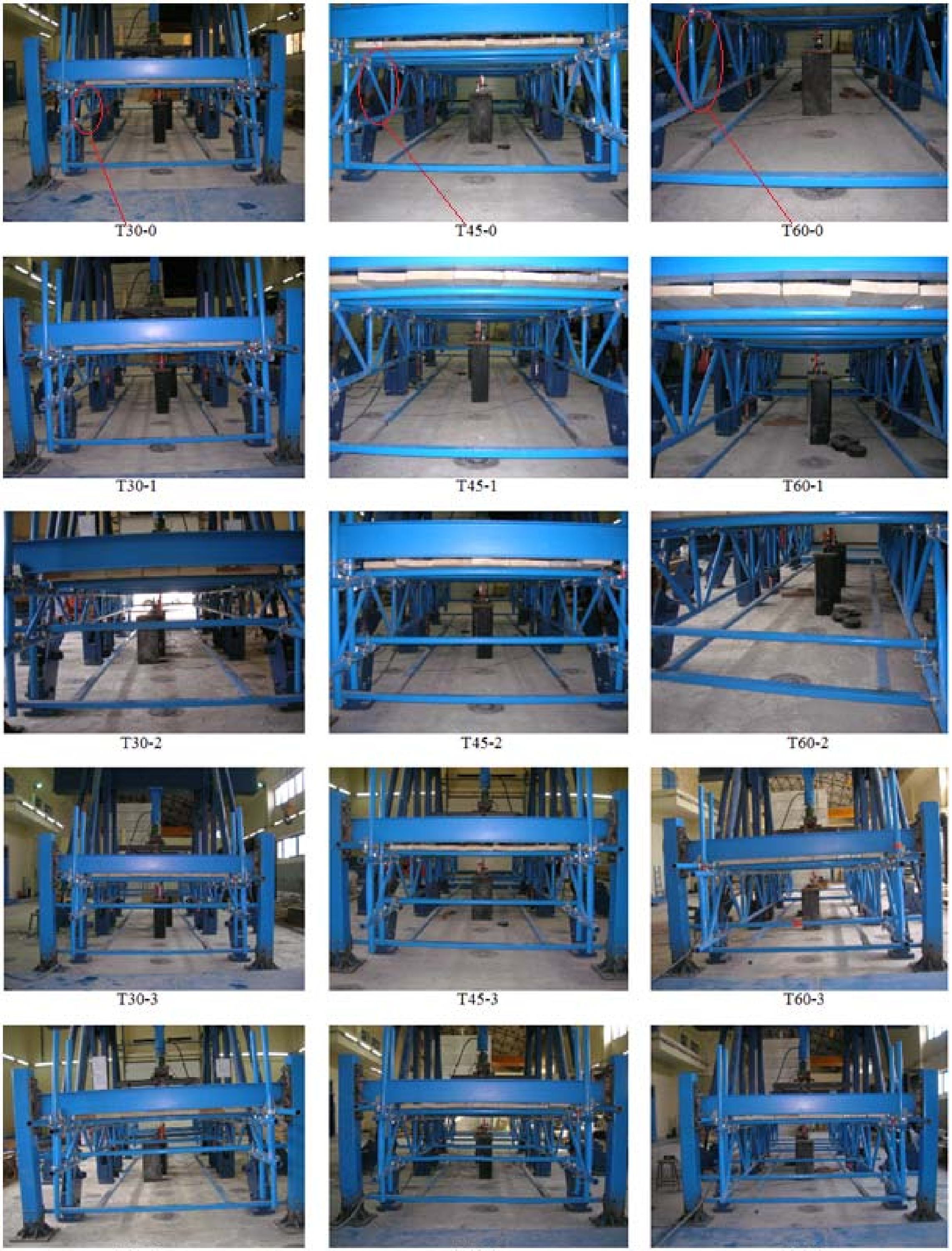


Figure 6. Locations of Linear Variable Differential Transducers on the Scaffolds during the Loading Tests



T30-0 T45-0 T60-0

T30-1 T45-1 T60-1

T30-2 T45-2 T60-2

T30-3 T45-3 T60-3

T30-5 T45-5 T60-5

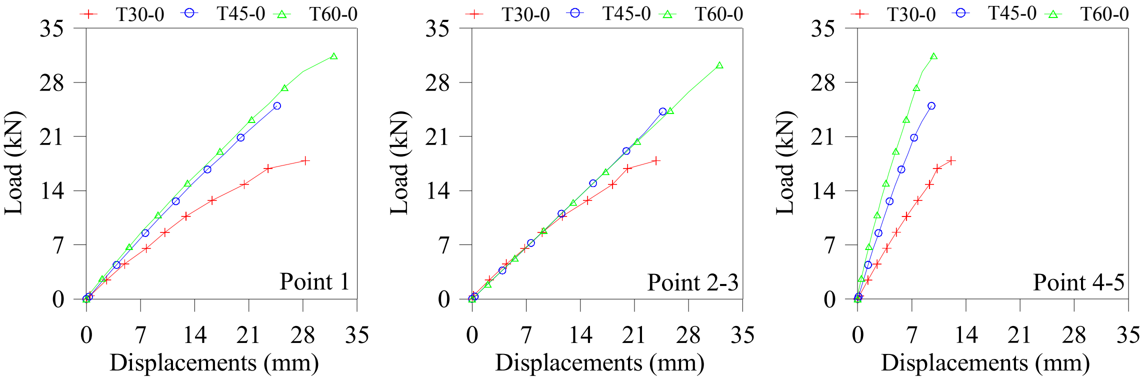
Figure 7. Photographs of the Loading Tests

a) Deformation of T30-0 System b) Deformation of T45-0 System c) Deformation of T60-0 System

Figure 8. Deformation of some scaffolding systems during the loading tests

3.3 Load–Displacement Curves

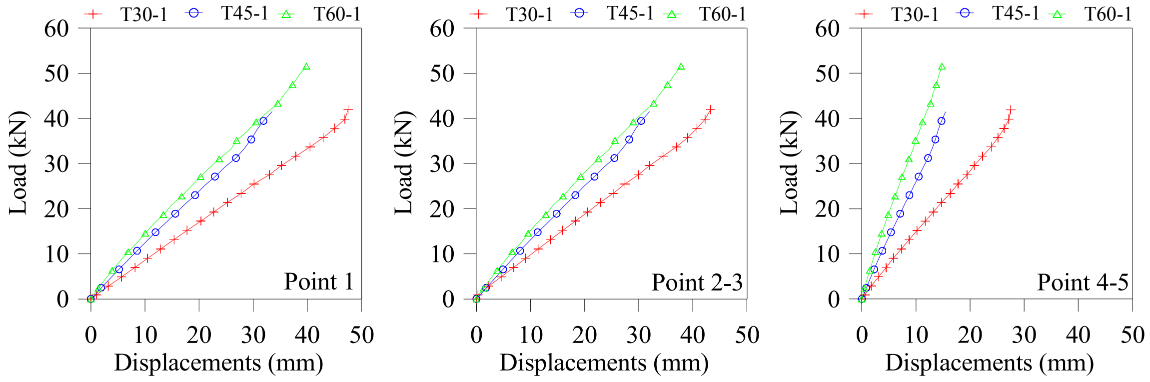
The load-displacement curves obtained from critical points of systems without tie bars (Point 1, average of displacements on Point 2-3 and average of displacements on Point 4-5, See Figure 6) are illustrated in Figure 9. Under the same load, the T30 systems showed the highest displacements among the systems studied. Displacements showed an increasing trend with increasing load. The displacements of the wooden boards and purlins (Points 1 and 2–3) of the T45 and T60 systems were similar. However, under the same load, the T60 systems showed the minimum truss displacements (Points 4–5) among the systems studied.



a) b) c)

Figure 9. Load–displacement Curves obtained from Critical Points of Scaffolds without Tie Bars: (a) Point 1 (b) Point 2–3 and (c) Points 4–5

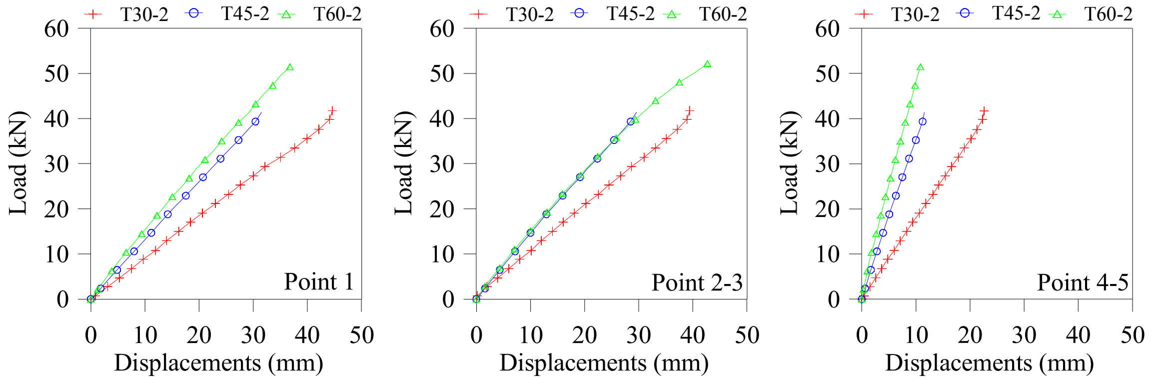
The load–displacement curves obtained from critical points of systems with one tie bar are demonstrated in Figure 10. The displacements obtained at critical points of the T30 systems were nearly two times larger than those of the T45 and T60 systems. In addition, the displacement change trends of the wooden boards and purlins of the T45 and T60 systems were similar. However, the displacements of the trusses of the T60 scaffolds were smaller than those of the T30 and T45 scaffolds.



a) b) c)

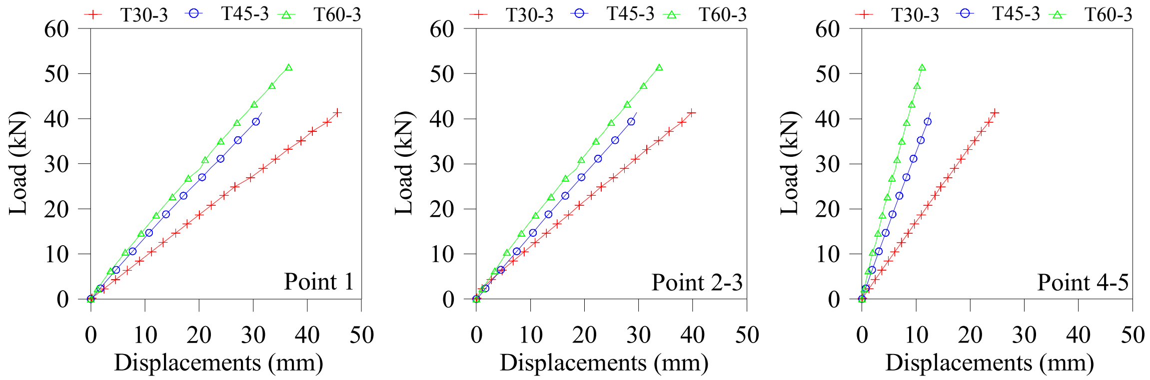
Figure 10. Load-displacement Curves obtained from Critical Points of Scaffolds with One Tie Bar: (a) Point 1 (b) Points 2–3 and (c) Points 4–5

The load–displacement curves obtained from critical points of systems with two, three, and five tie bars are shown in Figures 11, 12, and 13, respectively. The displacement results of these systems are similar to those indicated in Figs. 9 and 10, which means the displacements obtained at critical points of T30 are larger than those obtained at critical points of T45 and T60. Thus, the T45 and T60 systems can be inferred to be more rigid than the T30 systems.



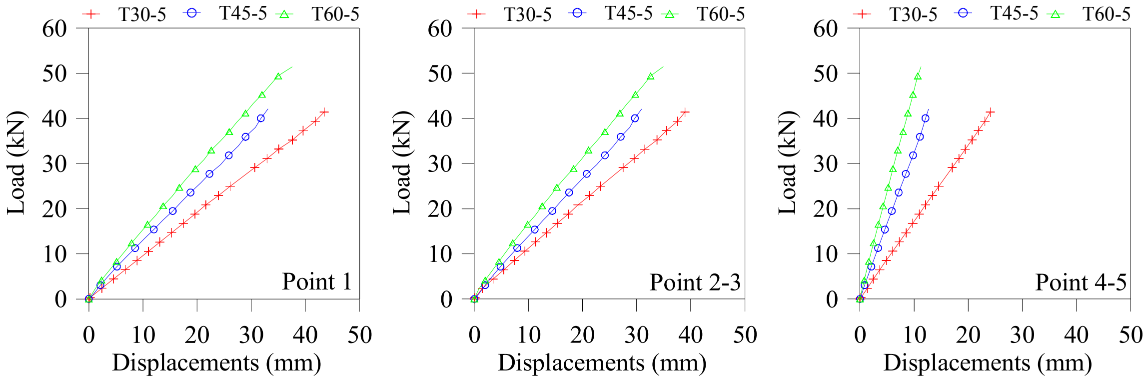
a) b) c)

Figure 11. Load–displacement Curves obtained from Critical Points of Scaffolds with Two Tie Bars: (a) Point 1 (b) Points 2–3 and (c) Points 4–5



a) b) c)

Figure 12. Load–displacement Curves obtained from Critical Points of Scaffolds with Three Tie Bars: (a) Point 1 (b) Points 2–3 and (c) Points 4–5

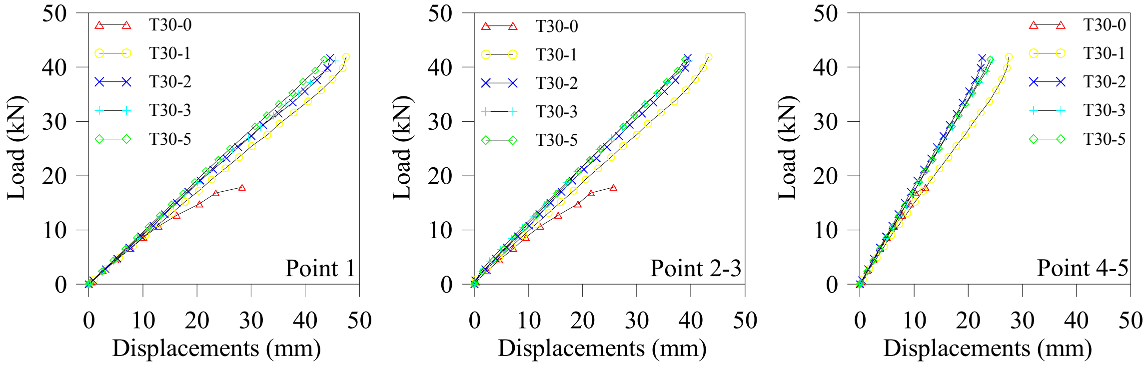


a) b) c)

Figure 13. Load–displacement Curves obtained from Critical Points of Scaffolds with One Five Bars: (a) Point 1 (b) Points 2–3 and (c) Points 4–5

Figures 9–13 demonstrate that displacements of the wooden floor were slightly larger than those of the purlins under all system conditions tested. However, the displacements obtained from the trusses under all system conditions studied were only about one-fourth of those observed in wooden floors and purlins. Truss displacements decreased from T30 to T45 and from T45 to T60.

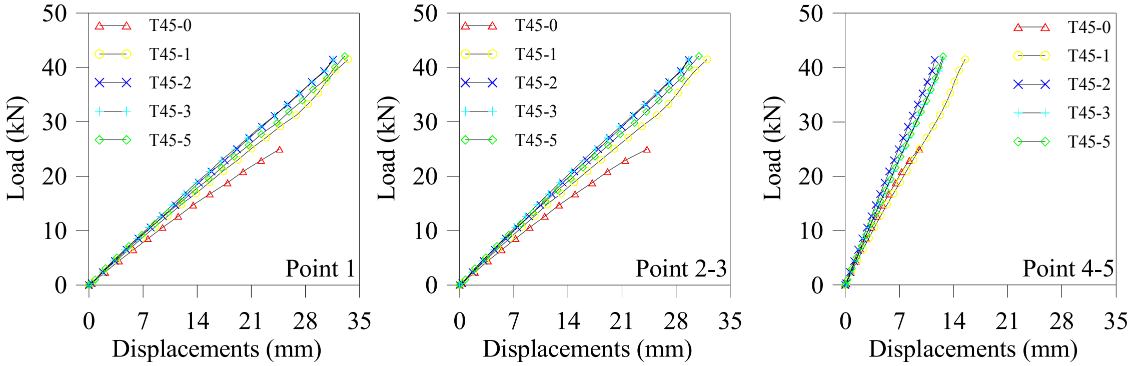
The load–displacement curves obtained from critical points of the T30 systems are illustrated in Figure 14. T30-0 and T30-1, which have no and one tie bar, respectively, showed larger displacements than other systems under the same load conditions. T30-2, T30-3, and T30-5 showed similar load–displacement curves. The displacements of the trusses (Points 4–5) were smaller than those of the purlins (Points 2–3) and wooden boards (Point 1). T30-0 behaved nonlinearly as its load increased. The maximum displacement of T30-1 (47.6 mm) occurred under a load of 41.9 kN at Point 1 (wooden board).



a) b) c)

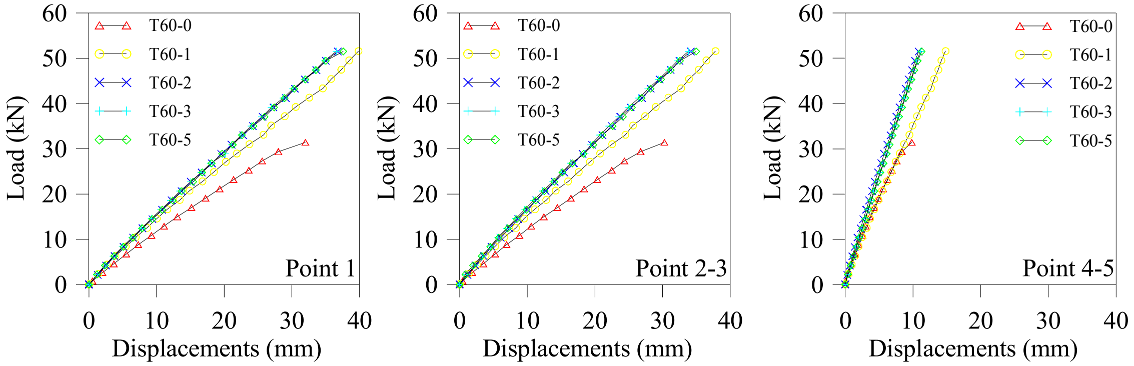
Figure 14. Load-displacement Curves obtained from the Critical Points of T30 Systems: (a) Point 1 (b) Points 2–3 and (c) Points 4–5

The load–displacement curves obtained from critical points of the T45 and T60 systems are illustrated in Figures 15 and 16, respectively. Displacements obtained at critical points of systems with no and only one tie bar are larger than those of other system s. T60-2 showed the lowest displacement among the scaffolds studied.



a) b) c)

Figure 15. Load-displacement Curves of the T45 Scaffold Measures from Various Critical Points: (a) Point 1 (b) Points 2–3 and (c) Points 4–5



a) b) c)

Figure 16. Load-displacement Curves of the T60 Scaffold Measured from Various Critical Points: (a) Point 1 (b) Points 2–3 and (c) Points 4–5

Table 1 shows the maximum displacements of all of the scaffolds under a maximum load. Table 2 is presented to understand the responses of the systems more clearly. In Table 2, displacements obtained from the critical points of all systems, except T30-0, T45-0, and T60-0, were calculated using the linear elasticity approach, under a constant loading 40 kN for all systems T30-0, T45-0, and T60-0, which present no tie bars, were excluded from these calculations because these scaffolds behaved nonlinearly after application of loads of 17, 25, and 30 kN, respectively. Table 2 clearly indicates that scaffolds with two and three tie bars present good behavior, thereby indicating sound structural safety. A bar chart is given in Figure 17 to show the differences of the data listed in Table 2. Figure 17 shows the displacements of all systems under 40 kN load obtained from critical points

Table 1. Displacements of All Systems under a Maximum Load

		L (kN)	D (mm)	L (kN)	D (mm)	L (kN)	D (mm)	L (kN)	D (mm)	L (kN)	D (mm)
		Number of Tie Bars									
		0		1		2		3		5	
T30	Point 1	17.9	28.3	41.9	47.6	41.7	44.6	41.3	45.6	41.4	43.5
	Point 2-3	17.9	23.8	41.9	43.3	41.7	39.4	41.3	39.7	41.4	38.9
	Point 4-5	17.9	12.1	41.9	27.5	41.7	22.6	41.3	24.5	41.4	24.1

T45	Point 1	25.0	24.7	41.5	33.5	41.4	31.6	41.4	31.6	42.1	33.1
	Point 2-3	25.0	24.7	41.5	32.0	41.4	29.6	41.4	29.6	42.1	30.9
	Point 4-5	25.0	9.5	41.5	15.5	41.4	11.6	41.4	12.6	42.1	12.7
T60	Point 1	31.4	32.0	51.6	39.9	51.5	36.8	51.5	36.6	51.5	37.6
	Point 2-3	31.4	32.0	51.6	37.8	51.5	33.5	51.5	33.8	51.5	35.0
	Point 4-5	31.4	9.8	51.6	14.8	51.5	10.8	51.5	11.1	51.5	11.3

Table 2. Displacements of All Systems under 40 kN Load

		L (kN)	D (mm)	L (kN)	D (mm)	L (kN)	D (mm)	L (kN)	D (mm)	L (kN)	D (mm)
		Number of Tie Bars									
		0		1		2		3		5	
T30	Point 1	40.0	-	40.0	45.4	40.0	42.8	40.0	44.2	40.0	42.0
	Point 2-3	40.0	-	40.0	41.3	40.0	37.8	40.0	38.5	40.0	37.6
	Point 4-5	40.0	-	40.0	26.3	40.0	21.7	40.0	23.7	40.0	23.3
T45	Point 1	40.0	-	40.0	32.3	40.0	30.5	40.0	30.5	40.0	31.5
	Point 2-3	40.0	-	40.0	30.8	40.0	28.6	40.0	28.6	40.0	29.4
	Point 4-5	40.0	-	40.0	14.9	40.0	11.2	40.0	12.2	40.0	12.1
T60	Point 1	40.0	-	40.0	30.9	40.0	28.6	40.0	28.4	40.0	29.2
	Point 2-3	40.0	-	40.0	29.3	40.0	26.0	40.0	26.3	40.0	27.2
	Point 4-5	40.0	-	40.0	11.5	40.0	8.4	40.0	8.6	40.0	8.8

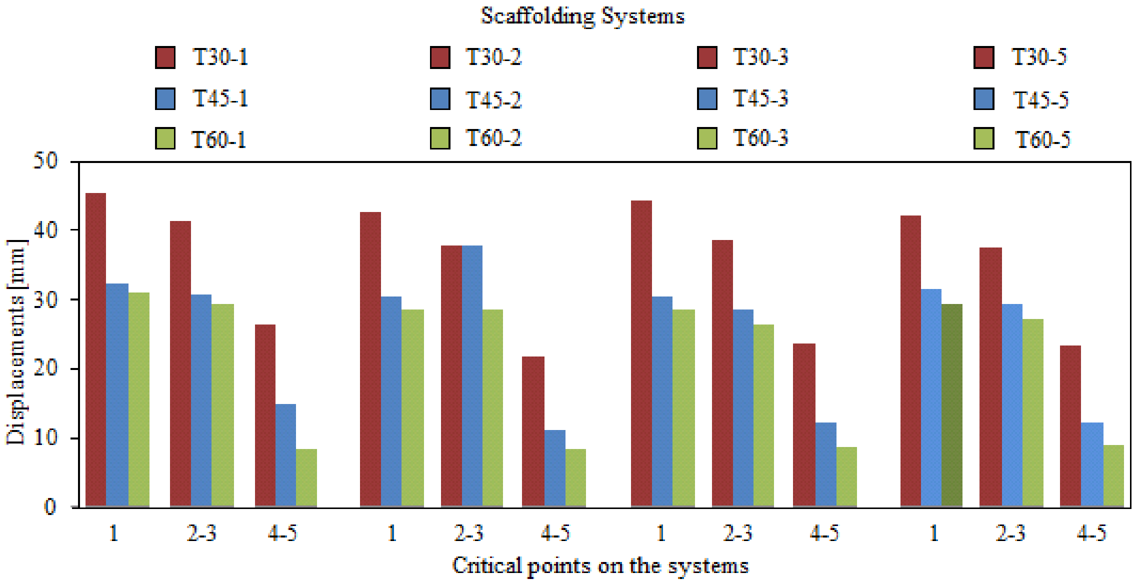


Figure 17. Displacements of All Systems under 40 kN Load obtained from Critical Points

4. CONCLUSIONS

This study experimentally evaluated the effects of number of tie bars on the structural behavior of suspended scaffolding systems. Fifteen suspended scaffolding systems with different truss heights and tie bar connections were constructed and loaded. Load–displacement curves were obtained and compared to determine the optimal suspended scaffolding system from the viewpoint of safety and cost-savings. The following conclusions were obtained:

- Among the systems studied, the T30 scaffolds with no and one tie bar showed the maximum displacements. T30-2, T30-3, and T30-5 showed smaller displacements than did T30-0 and T30-1. T30-0 behaved nonlinearly under a 17 kN load.
- The displacement change trends of the T45 and T60 systems were similar to those of the T30 systems, which means scaffolds with the same truss height show maximum displacements when they include no or only one tie bar. Scaffolds with two, three, and five tie bars showed minimal displacements. Scaffolds with no tie bar (i.e., T45-0 and T60-0) behaved nonlinearly under 25–30 kN loads.
- Displacements of the wooden floor were larger than those of the purlins, which, in turn, were larger than those of the trusses at all system conditions studied. The mechanism of load transfer appears to involve loads moving from the wooden floor to the purlins and then to the trusses, which are the main structural elements of scaffolds. Thus, the displacement results were consistent for all systems studied.
- The displacements of the T30 systems were much larger than those of the T45-and T60 systems. All of these systems, the T60 systems showed the minimum displacements.
- At the same truss height, scaffolds with two tie bars showed smaller displacements than scaffolds with no or only one tie bar. The displacements of these scaffolds were also nearly equal to or smaller than those of scaffolds with three and five tie bars.
- T60-2 showed the lowest displacements among the scaffolds studied under a 40 kN load.
- Considering the displacement responses of all scaffolds studied in this work, T60-2 showed the best rigidity and structural responses. While both T60-3 and T60-5 can satisfy safety requirements, the T60-2 system is recommended when safety and cost-savings are primary considerations.

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