EXPERIMENTAL STUDY ON LOAD CAPACITIES OF ISOLATED HEAVY-DUTY SCAFFOLDS USED IN CONSTRUCTION

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ABSTRACT: The isolated heavy-duty scaffolds, which have higher load capacity, are often considered to serve as the falsework during the construction stage of a building with high clearance, large spans and thick slabs in order to meet the load demand of the building. Because isolated heavy-duty scaffolds serve as temporary structures and are promptly dismantled after the construction is complete, their importance is often neglected. Until now, data regarding the structural design of isolated heavy-duty scaffolds has been rather scarce, and the assembly of isolated heavy-duty scaffolds on construction sites still relies mainly on the experience of construction workers. This phenomenon results in a high risk of collapse of isolated heavy-duty scaffolds actually applied on construction sites. This study explores the critical loads and the failure modes of isolated heavy-duty scaffolds in various setups by testing actual setups of isolated heavy-duty scaffolds on construction sites. The results show that, since the bending moment stiffness provided by the base screw jacks of isolated heavy-duty scaffolds is negligible, the base screw jack has a limited effect on the overall load capacity of isolated heavy-duty scaffolds. When isolated heavy-duty scaffolds are set up on ground with varying elevation or on ground under an inclined top slab with varying elevation, their load capacity is not substantially affected as long as the difference in elevation is less than 56 cm. When assembled in multiple layers on construction sites, isolated heavy-duty scaffolds are often erected with steel tube shores on the top layer. However, this combined scaffolding structure reduces the load capacity of isolated heavy-duty scaffolds by as much as 70%. In this case, directly extending the top screw jacks of the isolated heavy-duty scaffolds is better than using a combined scaffolding structure. As for the isolated heavy-duty scaffolds after being repeatedly used, this study uses a repeated loading test to simulate the lower bound strength of isolated heavy-duty scaffolds on construction sites. Contractors can choose an appropriate reduction factor based on cost and construction safety considerations when engineers design the strengths of reusable isolated heavy-duty scaffolds.

Keywords: Critical load, falsework, heavy-duty scaffold, steel shore

1. INTRODUCTION

Structures that require large spaces such as factory buildings, warehouses and gymnasiums tend to have high headroom, large spans and thick slabs. During construction of these building structures, door-type steel scaffolds and tubular steel adjustable shores are unsuitable for use as falseworks because of their low load capacity. Instead, isolated heavy-duty scaffolds are preferable because of their higher load capacity. Figure 1 shows the isolated heavy-duty scaffolds used during construction of a new factory building with high headroom in Taiwan.

Up to now, no specific design codes have provided design references for isolated heavy-duty scaffolds used on Taiwan construction sites. Therefore, effectively controlling variation in the load carrying capacities of various setups of isolated heavy-duty scaffolds is often difficult. The assembly of isolated heavy-duty scaffolds on construction sites often relies on the experience of construction workers. This phenomenon increases the risk of collapse in isolated heavy-duty scaffolds actually applied on construction sites. Thus, a clear understanding of the structural behaviors of these scaffolds is essential. Figure 2 shows a falsework that collapsed during grouting on a construction site in Kaohsiung, Taiwan.

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Figure 2. Falsework Collapse at a Construction Site in Taiwan

Until now, many construction falseworks have been studied. In terms of modular frame-type scaffolds, Weesner and Jones [1] performed numerical analyses and tests of frame-type steel scaffolding structures to explore the ultimate load carrying capacity of frame-type steel scaffolding structures. Their numerical analysis included both eigen buckling analysis and geometrically nonlinear analysis, and the tests were mainly loading tests.

In terms of modular door-type steel scaffolds, Yu *et al.* [2, 3, 4] explored the load capacities of modular door-type steel scaffolds. Similarly, they performed numerical analyses and loading tests to explore the relationship between layer number and load capacity in modular door-type steel scaffolds. Huang *et al.* [5, 6] performed numerical analyses and loading tests of door-type steel scaffolds to confirm the relationship between load capacity and layer number in door-type steel scaffolds. Their numerical analysis was performed using an eigenvalue solution. They also derived an analytical solution to establish an analytical model for door-type steel scaffolds.

Peng *et al.* [7, 8, 9, 10, 11] performed a theoretical analysis and experimental study of door-type steel scaffolding systems with varying setups and varying numbers of layers. The theoretical analysis used an analytical solution to establish simplified models of door-type steel scaffolding systems, and the numerical analysis mainly applied second-order elastic with semi-rigid joint analysis. In addition to comparing load capacities between a steel scaffolding system alone and a steel scaffolding system combined with wooden shores, they also compared failure modes between these two systems. Additionally, Kuo *et al.* [12] and Peng *et al.* [13] compared the effects of various loading paths and loading patterns on the load capacities of door-type steel scaffolding systems and analyzed the effects of influence lines on these loads. Additionally, Peng *et al.* [14, 15] also investigated the structural behaviors of modular scaffolds used for finishing of the façade of buildings based on a series of experimental tests and numerical analyses.

In terms of the study of tube and couple scaffolds, Liu *et al.* [16] conducted experimental study on full-scale large-sized tube and couple scaffolds without X-bracing and explored the structural behaviors of the whole tube and couple scaffolding system after loading. In terms of the study of system scaffolds, Peng *et al.* [17] conducted numerical analysis and experimental study to explore the load capacities and failure modes of system scaffolds with different setups. In terms of the reliability and the probabilistic studies of steel scaffolds, Zhang *et al.* [18, 19] conducted the reliability analyses of the scaffolding systems and explored the variability of parameters related to the use of steel scaffolds, such as semi-rigid stiffness, load eccentricities and initial geometric imperfections.

The above researches show that falsework-related studies have mainly focused on the temporary supports for frame-type steel scaffolds, door-type steel scaffolds, tube and couple scaffolds, and system scaffolds. Studies of isolated heavy-duty scaffolds are relatively rare. Since the dimensions and the assemblies of isolated heavy-duty scaffolds substantially differ from those of other scaffolds, previous falsework-related studies can serve only as references and are not directly applicable to isolated heavy-duty scaffolds. Therefore, the load capacities and failure models of isolated heavy-duty scaffolds require further study.

2. RESEARCH OBJECTIVE AND TEST PLANNING

2.1 Research Objective

This study explored the load carrying capacities and failure modes of isolated heavy duty scaffolds by comparing the loading test results of various setups of isolated heavy-duty scaffolds actually used on construction sites. Hopefully, the results of this study can be directly used in the construction industry as a reference for strength design of isolated heavy-duty scaffolds. Serving as temporary structures during the construction stage, the isolated heavy-duty scaffolds used on construction sites have diverse setups and qualities. Thus, this preliminary research appropriately focuses on loading tests in order to realize the actual failure models of isolated heavy-duty scaffolds. After that, the further analytical study will be conducted based on these test results.

2.2 Test Planning

Five main tests were performed in isolated heavy-duty scaffolds: (1) the effect of stiffness of base screw jacks on load capacity, (2) the effect of top slope and inclined ground on load capacity, (3) the effect of extension of top and base screw jacks on load capacity, (4) the effect of steel tube shores added at the top of isolated heavy-duty scaffolds on load capacity, (5) the lower limit of load capacity of reusable scaffolds. The procedures for performing the tests are summarized below.

2.2.1 Two-layer basic setup

This test explored the load capacities and failure modes of a basic two-layer setup for isolated heavy-duty scaffolds. The test results can be used to compare with those of other setups of isolated heavy-duty scaffolds used in this study. In the two-layer basic setup, the height of each layer is 150 cm, and the height of both top and base screw jacks is 20 cm. The scaffolds are reinforced with plane braces as shown in Figure 3.

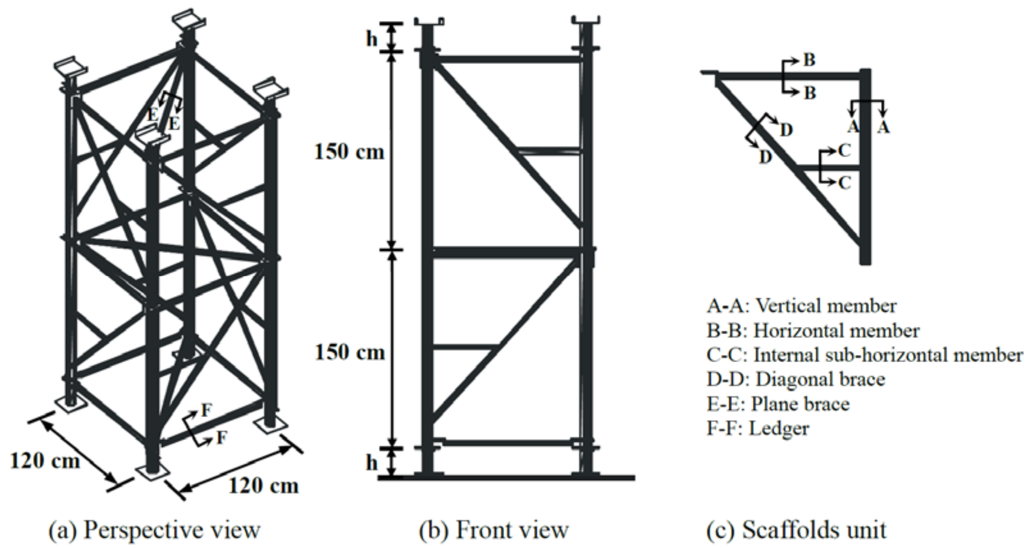
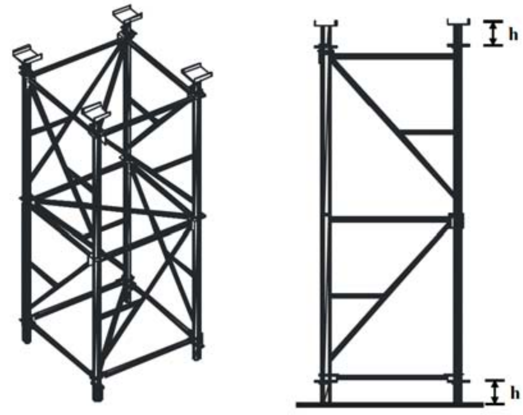


Figure 3. Test configuration for Two-layer Basic Setup and Cross-sectional Positions of Isolated Heavy-duty Scaffold Unit

2.2.2 Two-layer basic setup with non-stiffened base screw jacks

To determine how the stiffness of base screw jacks affects the load capacity, a two-layer basic test setup was used with the base plates of the base screw jacks cut off so that, when the deformation and failure of the scaffolds occur, the base screw jacks would not provide additional bending moment stiffness. In further analyses, the boundary condition of this base screw jack without the base plate can be considered as a hinge joint. Figure 4 shows the test configuration.



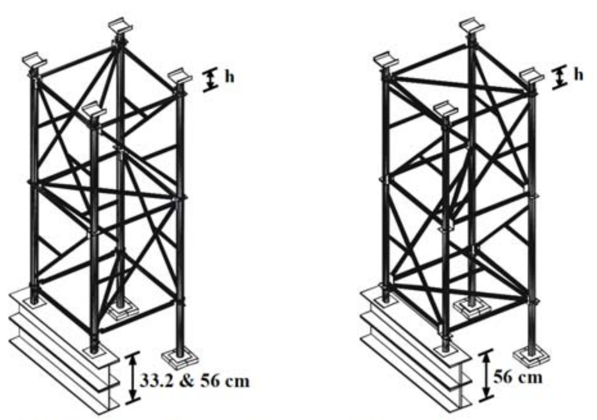
(a) Perspective view (b) Front view

Figure 4. Test Configuration of Two-layer Basic Setup with Non-stiffened Base Screw Jacks

2.2.3 Difference in ground elevation

Driveways or stairways in a building often require the scaffolds setup on ground with varying elevation during the construction stage. This test explores how varying ground elevation affects the load capacities and failure modes of isolated heavy-duty scaffolds. Scaffolds on two different elevations (33.2 cm and 56 cm) are tested. The two elevations 33.2 cm and 56 cm are based on the inclinations of the ground which are 15.5 degrees and 25 degrees, respectively. With the width of the scaffold 120 cm, the elevation 33.2 cm is equal to 120 cm multiplied by tan (15.5°) and the elevation 56 cm is equal to 120 cm multiplied by tan (25°).Figure 5(a) shows the test configuration for scaffolds erected on ground with two different elevations.

In the test configuration for a 33.2 cm difference in elevation, the height of the front row base screw jacks is adjusted to 20 cm, and that of the back row base screw jacks is adjusted to 53.2 cm (=33.2+20). Each scaffold layer is 150 cm high, and both layers are reinforced with plane braces. The height of top screw jacks is adjusted to 20 cm. The test configuration for the 56 cm difference in ground elevation is the same as the test configuration for the 33.2 cm difference in ground elevation with the exception of the back row base screw jacks, which are adjusted to 76 cm (=56+20).



(a) Difference in ground elevation (b) Top difference in elevation (Upside down scaffold setup)

Figure 5. Test Configuration of Two-layer Setup with Difference in Elevation between Top and Ground

2.2.4 Top difference in elevation

To cope with the height of roof beams or slabs during the construction of a building, scaffolding height may differ because of varying heights of roof beams or slabs. A 56 cm difference in scaffolding height was tested. Since the steel loading-holder is on the top of the oil pressure machine, configuring scaffolds with top difference in elevation was very difficult in the laboratory. The solution was to simulate the top difference in elevation of the scaffolds on the ground by performing the tests with the scaffolding structure assembled upside down. In the test configuration for scaffolds with 56 cm top difference in elevation, other than the scaffolding structure is put upside down, the remaining structures were measured using the same test configuration used for the 56 cm difference in ground elevation, including all screw jacks and blocks (as described in the previous section). Figure 5(b) shows the test configuration.

2.2.5 Extension of top screw jacks

Since each layer is 1.5 m high, the total height of a multiple-layer isolated heavy-duty scaffold is often insufficient for the full headroom of the interior of a construction structure. In this case, extending the top screw jacks to fill the gap is advised. Figure 6 shows the test configuration.

Two-layer isolated heavy-duty scaffolds are tested. The top screw jacks of the scaffolds are extended to 75 cm, and the height of the base screw jacks is 20 cm. The height of each layer of the scaffolds is 150 cm, and both layers are reinforced with plane braces.

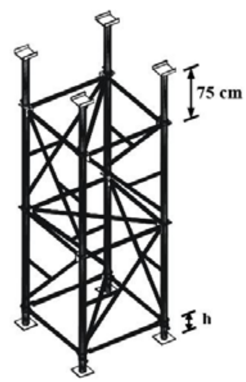


Figure 6. Test Configuration of Two-layer Setup with Extension of Top Screw Jacks

2.2.6 Extension of both top and base screw jacks

To solve the problem discussed above regarding the gap between the scaffolds and slab, the base screw jacks should also be extended when the extended top screw jacks cannot fill up the gap. In other words, both the top and base screw jacks should be extended to fill the gap between the scaffolds and slabs (Figure 7). The test configuration extends both the top and base screw jacks of the two-layer isolated heavy-duty scaffolds to 75 cm, respectively. Each scaffold layer is 150 cm high, and both layers are reinforced with plane braces.

2.2.7 Steel tube shores with and without enclosed restraint on top of the scaffolds

Similarly, the above problem of the gap between the scaffolds and slabs observed during the site investigation is often solved by adding steel tube shores on top of the scaffolds to fill the gap between the scaffolds and slab. The steel tubes can also be reinforced by horizontal enclosed restraint with stringers. This study tested the load capacities and failure modes of this combined scaffolding structure, *i.e.*, steel tube shores added to the top of isolated heavy-duty scaffolds. Figure 8 shows the test configuration of the scaffolds reinforced with steel tube shores without enclosed restraint. Figure 9 shows the test configuration of the scaffolds reinforced with steel tube shores with enclosed restraint.

For the test configuration of the scaffolds reinforced with steel tube shores without enclosed restraint, the scaffold assembly is identical to that in the basic two-layer setup described above. This study simulated the configuration actually used on construction sites by placing two I-beams (200 cm long, 15 cm high) on the top screw jacks of the scaffolds. Four steel tube shores (44 cm in length) are mounted on top of the I-beams by clamps as shown in Figure 9. Both the top and bottom ends of the steel tube shores are fixed with screw jacks of door-type steel scaffolds, with the bottom end fixed on the I-beams by four clamps and with the top ends sticking against the loading-holder of the test machine. The screw jack of the door-type steel scaffolds is 5 cm, and the length inserted into the steel tube of scaffolds is 10 cm.

The scaffolds reinforced with steel tube shores "with" and "without" enclosed restraints are configured similarly. The only difference is that four reinforced horizontal stringers for the "with" case are fixed with swivel couplers at the centers of the steel tube shores on top of the scaffolds.

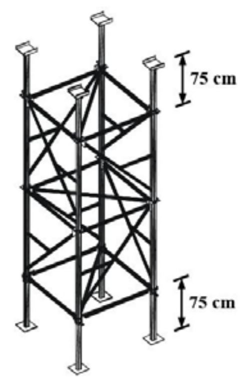


Figure 7. Test Configuration of Two-layer Setup with Extension of Both Top and Base Screw Jacks

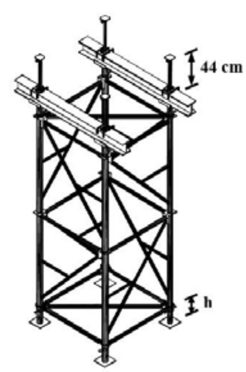


Figure 8. Test Configuration of Two-layer Setup Reinforced with Steel Tube Shores without Enclosed Restraint

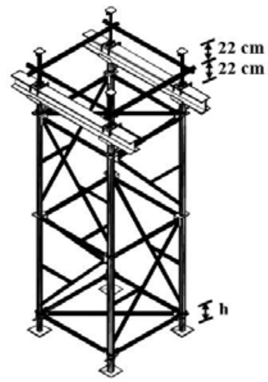


Figure 9. Test Configuration of Two-layer Setup Reinforced with Steel Tube Shores with Enclosed Restraint

2.2.8 Lower strength bound of reusable scaffolds

On construction sites, the isolated heavy-duty scaffolds are usually assembled with reusable scaffolds. To obtain the load capacity of these reusable scaffolds in the worst condition, reloading the scaffolds is advised. A second loading is performed after finishing the first loading and then readjusting the scaffolds. When the first-loading test finishes and unloads, the deformed scaffolds are reinstalled and their setups are based on those of the first-loading tests as far as possible. This study defines the re-installed process of scaffolds as the readjusting. The load capacity of the scaffolds obtained at the second loading can be considered the lower limit of the load capacity of reusable scaffolds. The quotient obtained by dividing the lower limit value of load capacity of the second loading by that of the first loading gives the reduction in the strength of the reusable isolated heavy-duty scaffolds.

3. CROSS-SECTIONAL DIMENSIONS AND MATERIAL PROPERTIES

Figures 3(a) and 3(c) give the cross-sectional positions measured in multiple sets of isolated heavy-duty scaffolds where A-A is the vertical member of the scaffold unit: D (diameter) = 76.5 ± 0.5mm, t (thickness) = 3.2 ± 0.1mm; B-B is the horizontal member of the scaffold unit: D = 40.2 ± 0.2mm, t = 2.1 ± 0.1mm; C-C is the internal sub-horizontal member of the scaffold unit: D = 33.4 ± 0.1mm, t = 2.0 ± 0.1mm; D-D is the diagonal brace of the scaffold unit: D = 33.4 ± 0.1mm, t = 1.8 ± 0.1mm; E-E is the plane brace: D = 42.3 ± 0.1mm, t = 1.9 ± 0.1mm; F-F is the ledger: D = 42.4 ± 0.2mm, t = 2.4 ± 0.2mm. Three scaffold units were randomly selected for elastic modulus test of the materials. The average value of elastic modulus of the scaffold units was 19,982kN/cm^2, which approximates the nominal value of 20,012.4kN/cm^2.

4. RESULTS AND DISCUSSIONS

4.1 Two-layer Basic Setup

The two tests (A and B) performed for this setup showed that the failure loads of the isolated heavy-duty scaffolds are 894.003 kN and 920.688 kN, respectively, and that the vertical deformations of the scaffolds under maximum loads are 20.575 mm and 21.208 mm, respectively. Table 1 shows the test results.

Figure 10 shows the P-Δ curve (curve of loads and vertical deformations) for the results of test A under the first and second loadings. The curve for the first loading shows that the load and deformation relationship increases linearly. When the load increases to the maximum value of 894.003 kN, the vertical deformation is 20.575 mm. After the buckling failure occurs, the load decreases rapidly. Figure 11 shows the failure mode of the scaffolds. The left-rear vertical member of the first layer and the right-rear vertical member of the second layer are severely deformed, and an inclination in the top screw jacks results from severe deformation of the vertical members.
After the first loading, the scaffolds were unloaded and then readjusted. After these, we applied the second loading to simulate the load capacity of the reusable scaffolds in the worst case. The maximum load capacities obtained in tests A and B are 288.316 kN and 653.534 kN, respectively, and the corresponding vertical deformations are 26.025 mm and 21.750 mm, respectively. The failure modes of the second loading resemble those of the first loading. Figure 10 shows the comparatively flat P-Δ curve obtained in the second loading, which substantially differs from that observed in the first loading. However, vertical deformations are similar in the first and second loadings under maximum load (approximately 2 cm).

Table 1 shows that the average maximum load capacity of the two-layer basic setup scaffolds is 907.346 kN and that the average corresponding vertical deformation is 20.892 mm. The average maximum load capacity of the second loading is 470.925 kN, which is 52% of that of the first loading (=470.925/907.346). The experimental results obtained for this basic setup of isolated heavy-duty scaffolds were then used for the control setup in further tests of other configurations.

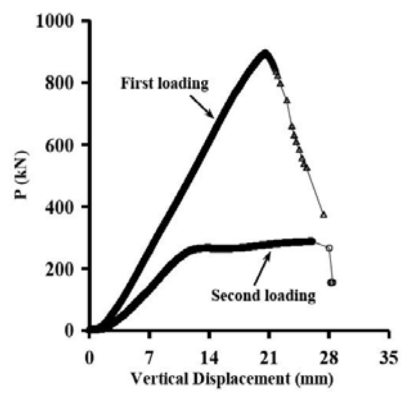


Figure 10. P-Δ Curves of Two-layer Basic Setup under the First and Second Loadings in Test A

4.2 Two-layer Basic Setup with Non-stiffened Base Screw Jacks

The test configurations for the two-layer basic setup scaffolds with non-stiffened base screw jacks are identical to those for the two-layer basic setup scaffolds. The only difference is that the non-stiffened base screw jacks are used in these test configurations. That is, the base plate of the base screw jacks is removed so that the jacks do not provide additional bending moment stiffness. Three tests were performed (tests A, B and C). In tests A, B, and C, the maximum load capacities obtained in the first loading are 762.584 kN, 912.560 kN and 899.974 kN, respectively, and the corresponding vertical deformations are 18.319 mm, 20.479 mm and 22.371 mm, respectively. Table 1 shows the test results.

Figure 12 shows the P-Δ curves observed in test A under the first and second loadings. The curve for the first loading shows a linear increase in the load and deformation relationship. At the maximum load of 762.584 kN, the corresponding vertical deformation is 18.319 mm, and buckling failure of the scaffolds occurs immediately. The right-front vertical member of the first layer deforms severely. Figure 13 shows the failure mode of the scaffolds.

Figure 11. Failure Mode A of Two-layer Basic Setup in Test

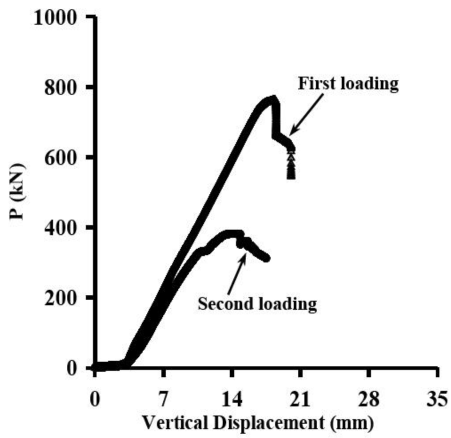
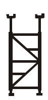
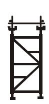


Figure 12. P-Δ Curves of Two-layer Basic Setup with Non-stiffened Base Screw Jacks under the First and Second Loadings in Test A

Figure 13. Failure Mode of Two-layer Setup with Non-stiffened Base Screw Jacks

The maximum load capacities of second loading of tests A, B and C are 382.272kN, 577.229 kN and 623.155 kN, respectively, and the corresponding vertical deformations are 14.200 mm, 15.225 mm and 17.387 mm. The failure modes are similar to those of the first loading. Figure 12 shows that the P-Δ curve obtained under the second loading resembles that observed under the first loading.

Table 1. Results of Loading Tests of Isolated Heavy-duty Scaffolds with Various Configurations

Type	Figure	Test number and (DIE type)	Max. load capacity / Corr. deformation	Test groups (load capacity test value [kN], deformation [mm])					
				Group A	Group B	Group C	Group D	Group E	Average value
Two-layer basic setup		B2HS (△h=0)	1st loading, capacity (2nd loading, capacity)	894.003 (288.316)	920.688 (653.534)	---	---	---	907.346 (470.925)
			1st loading, deformation (2nd loading, deformation)	20.575 (26.025)	21.208 (21.750)	---	---	---	20.892 (23.888)
Two-layer basic setup with non-stiffened base screw jacks		NB2HS (△h=0)	1st loading, capacity (2nd loading, capacity)	762.584 (382.272)	912.560 (577.229)	899.974 (623.155)	---	---	858.373 (527.552)
			1st loading, deformation (2nd loading, deformation)	18.319 (14.200)	20.479 (15.225)	22.371 (17.387)	---	---	20.390 (15.604)
Difference in ground elevation		JHSG(33.2) (△h=33.2)	1st loading, capacity (2nd loading, capacity)	911.671 (515.991)	862.262 (539.247)	---	---	---	886.967 (527.619)
			1st loading, deformation (2nd loading, deformation)	19.450 (13.412)	20.800 (14.731)	---	---	---	20.125 (14.072)
		JHSG(56) (△h =56)	1st loading, capacity (2nd loading, capacity)	875.120 (565.270)	905.383 (720.106)	---	---	---	890.252 (642.688)
			1st loading, deformation (2nd loading, deformation)	20.600 (15.283)#	21.288 (27.163)#	---	---	---	20.944 (21.223)
Top difference in elevation		PHSU(56) (△h =56)	1st loading, capacity (2nd loading, capacity)	998.337 (720.458)	883.406 (496.046)	---	---	---	940.872 (608.252)
			1st loading, deformation (2nd loading, deformation)	21.475 (17.500)	20.319 (15.987)	---	---	---	20.897 (16.744)
Extension of top screw jacks		U_J75HS Ext. 75cm (△h =0)	1st loading, capacity (2nd loading, capacity)	912.533 (613.863)	846.912 (530.194)	780.047 (490.530)	824.617 (609.762)	---	841.027 (561.087)
			1st loading, deformation (2nd loading, deformation)	22.338 (20.419)	21.425 (19.288)	24.463 (24.213)	21.338 (17.775)	---	22.391 (20.424)
Extension of both top and base screw jacks		U_J75J75HS Ext. 75cm (△h =0)	1st loading, capacity (2nd loading, capacity)	813.937 (266.141)	878.900 (365.079)	963.234 (212.806)	672.834 (370.881)	849.996 (298.410)	835.780 (302.663)
			1st loading, deformation (2nd loading, deformation)	21.700 (20.125)	21.538 (22.000)	23.663 (28.913)	20.006 (15.537)	21.750 (18.881)	21.731 (21.091)
Steel tube shores without enclosed restraint		US_S44HS tube length 44cm (△h =0)	Load capacity	231.210	234.283	---	---	---	232.747
			Deformation	47.689	45.114	---	---	---	46.402
Steel tube shores with enclosed restraint		US_{SG}44HS tube length 44cm (△h =0)	Load capacity	220.610	207.607	---	---	---	214.108
			Deformation	23.836	28.651	---	---	---	26.244

Notes:
1. Figures in brackets represent the results of the second loading.
2. Without specification, all the test configurations have top and base screw jacks.
3.--- : There is no test value.
4.△h : difference in elevation (cm)
5. # : Since the deformation cannot be restored after the first loading, the deformation of the second loading is considered the relative value.

The tests of the two-layer basic setup scaffolds with non-stiffened base screw jacks showed that the average maximum load capacity is 858.373 kN and that the average corresponding vertical deformation is 20.390 mm. The average maximum load capacity of the second loading is 527.552 kN, and the average corresponding vertical deformation is 15.604 mm. The average maximum load capacity of the second loading is 61% (=527.552/858.373)of that of the first loading.

Table 1 shows that the average maximum load capacity of the two-layer setup scaffolds with non-stiffened base screw jacks is 858.373 kN. Comparing with the average maximum load capacity of the two-layer basic setup scaffolds (907.346 kN), the strength of the two-layer basic setup scaffolds with non-stiffness base screw jacks is 95% (=858.373/907.346) of that of the two-layer basic setup scaffolds. That is to say, the bending moment stiffness added by the base screw jacks to the overall scaffold is negligible. This insignificant bending moment results mainly from the short height of the base screw jacks (20 cm) and the placement of the ledgers above the base screw jacks to prevent their deformation. Therefore, with or without the base plates under the base screw jacks, the load capacity of the scaffolds is not substantially affected.

4.3 Difference in Ground Elevation

4.3.1 33.2 cm difference in ground elevation

Two tests (tests A and B) of differences in ground elevation were performed. The maximum load capacities obtained in tests A and B under the first loading are 911.671 kN and 862.262 kN respectively, and the corresponding vertical deformations are 19.450 mm and 20.800 mm. Table 1 shows the test results.

Figure 14 shows the P-Δ curves of the first and second loadings on scaffolds with 33.2 cm difference in ground elevation in test A. The curve obtained for the first loading shows a linear increase in the load and deformation relationship. The maximum load capacity is 911.671 kN, and the corresponding vertical deformation is 19.450 mm. Figure 15 shows the failure mode of the scaffolds.

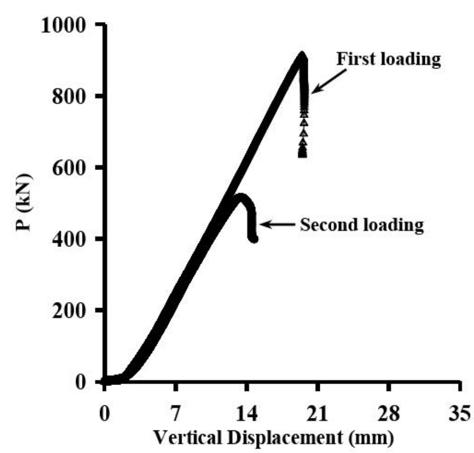


Figure 14. P-Δ Curves of Two-layer Setup with 33.2 cm Difference in Ground Elevation under the First and Second Loadings in Test A

The maximum load capacities of second loading of tests A and B are 515.991 kN and 539.247 kN, respectively, and the corresponding vertical deformations are 13.412 mm and 14.731 mm, respectively. Again, the failure modes resemble those observed in the first loading. Figure 14 shows that the P-Δ curve was similar under the first and second loadings.

Under the first loading, Table 1 shows that the average maximum load capacity of the two-layer scaffolds with 33.2 cm difference in ground elevation is 886.967 kN, and the average corresponding vertical deformation is 20.125 mm. The average maximum load capacity in the second loading is 527.619 kN, and the average corresponding vertical deformation is 14.072 mm. To put it another way, the load capacity of the scaffolds in the second loading is 59% (=527.619/886.967)of that of the first loading. Comparisons showed that the 886.967 kN average maximum load capacity of the two-layer scaffolds with 33.2 cm difference in ground elevation was 98%(=886.967/907.346) of the 907.346 kN maximum load capacity of the two-layer basic setup scaffolds. That implies that the effect of the 33.2 cm difference in ground elevation on the load capacity of isolated heavy-duty scaffolds is not statistically significant.

Figure 15. Failure Mode of Two-layer Setup with 33.2 cm Difference in Ground Elevation

4.3.2 56 cm difference in ground elevation

Tests A and B were performed similarly. The maximum load capacities of the first loading are 875.120 kN and 905.383 kN, respectively, and the corresponding vertical deformations are 20.600 mm and 21.288 mm. Table 1 shows the test results.

Figure 16 shows the P-Δ curves for the first and second loadings on scaffolds with 56 cm difference in ground elevation in test A. Under the maximum load capacity of 875.120 kN, vertical deformation is 20.600 mm. The right-front vertical member of the first layer is severely deformed, and the screw jacks show inclinations resulting from severe deformation of vertical members. Figure 17 shows the failure mode of the scaffolds.

The maximum load capacities of second loading of tests A and B are 565.270 kN and 720.106 kN, respectively, and the corresponding vertical deformations are 15.283 mm and 27.163 mm. The failure modes resemble those observed under the first loading. Figure 16 shows the similar P-Δ curves observed under the first and second loadings.

The above tests of the two-layer scaffolds with 56 cm difference in ground elevation under the first loading showed that the average maximum load capacity is 890.252 kN and that the average corresponding vertical deformation is 20.944 mm. The average maximum load capacity in the second loading is 642.688 kN, and the corresponding average vertical deformation is 21.223 mm. The load capacity of the scaffolds in the second loading is 72% (=642.688/890.252) of that in the first loading.

Comparing with the average maximum load capacity of the two-layer basic setup scaffolds (907.346 kN), the average maximum load capacity of the two-layer scaffolds with 56 cm difference in ground elevation (890.252 kN) is 98% (=890.252/907.346) of that of the basic setup. Therefore, when the screw jacks are extended to 76 cm on one side, the effect of the 56 cm difference in ground elevation on the load capacity of isolated heavy-duty scaffolds is negligible.

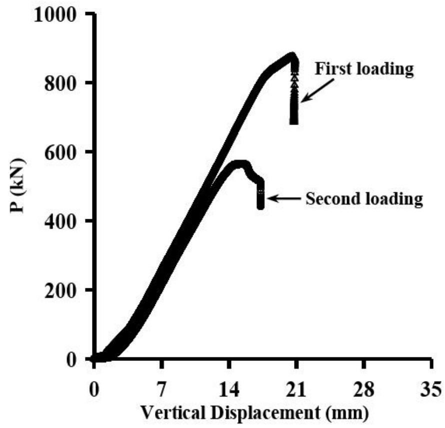


Figure 16. P-Δ Curves of Two-layer Setup with 56 cm Difference in Ground Elevation under the First and Second Loadings in Test A

Figure 17. Failure Mode of Two-layer Setup with 56 cm Difference in Ground Elevation

4.4 Top Difference in Elevation

The tests were performed in two groups (A and B). Table 1 shows the test results. The maximum load capacities for groups A and B under the first loading are 998.337 kN and 883.406 kN, respectively, and the corresponding vertical deformations are 21.475 mm and 20.319 mm.

Figure 18 shows the P-Δ curves obtained in test A of the first and second loadings on scaffolds with 56 cm top difference in elevation. The maximum value of load capacity is 998.337 kN, and the corresponding vertical deformation is 21.475 mm. The left-rear vertical member of the first layer and the right-rear vertical member of the second layer are severely deformed, and the screw jacks show an inclination resulting from severe deformation of vertical members. Figure 19 shows the failure mode of the scaffolds.

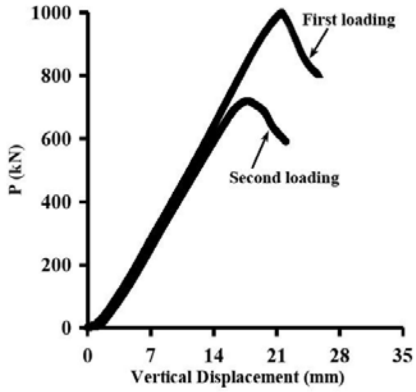


Figure 18. P-Δ Curves of Two-layer Setup with 56 cm Difference in Top Elevation under the First and Second Loadings in Test A

Figure 19. Failure Mode of Two-layer Setup with 56 cm Difference in Top Elevation

The maximum load capacities of second loading of tests A and B are 720.458 kN and 496.046 kN, respectively, and the corresponding vertical deformations are 17.500 mm and 15.987 mm. Again the failure modes resemble those obtained in the first loading. Figure 18 shows the similar P-Δ curves obtained in the first and second loadings.

The above tests showed that, under the first loading, the two-layer scaffolds with 56 cm top difference in elevation had an average maximum load capacity of 940.872 kN and an average corresponding vertical deformation of 20.897 mm. Under the second loading, the average maximum load capacity is 608.252 kN, which is 65% (=608.252/940.872) of that under first loading, and the average corresponding vertical deformation is 16.744 mm.

Comparing with the average maximum load capacity of the two-layer basic setup scaffolds (907.346 kN), the average maximum load capacity of the two-layer scaffolds with 56 cm top difference in elevation (940.872 kN) is 104% (=940.872/907.346) of that of the basic setup. This result can be attributed to the test error. This infers that when the top screw jacks are extended to 76 cm on one side, the effect of 56 cm top difference in elevation has a negligible effect on the load capacity of the isolated heavy-duty scaffolds.

4.5 Extension of Top Screw Jacks

This case included four tests (A, B, C and D). The maximum load capacities observed in four tests under first loading are 912.533 kN, 846.912 kN, 780.047 kN and 824.617 kN, respectively, and the corresponding vertical deformations are 22.338 mm, 21.425 mm, 24.463 mm and 21.338 mm. Table 1 shows the test results.

Figure 20 shows the P-Δ curves of the first and second loadings on scaffolds with top screw jacks extended in test A. The curve for the first loading shows that the load and deformation relationship increases linearly. At the maximum load of 912.533 kN, the corresponding vertical deformation is 22.338 mm. The two vertical members on the rear row of the first layer deform severely, and the screw jacks show an inclination resulting from severe deformation of the vertical members. Figure 21 shows the failure mode of the scaffolds.

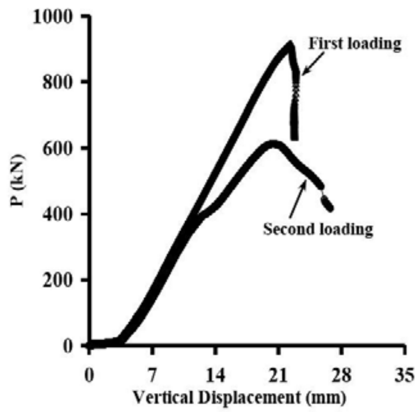


Figure 20. P-Δ Curves of Two-layer Setup with Extension of Top Screw Jacks under the First and Second Loadings in Test A

Figure 21. Failure Mode of Two-layer Setup with Extension of Top Screw Jacks

The maximum load capacities of second loading of tests A, B, C and D are 613.863 kN, 530.194 kN, 490.530 kN and 609.762 kN, respectively, and the corresponding vertical deformations are 20.419 mm, 19.288 mm, 24.213 mm and 17.775 mm. Basically, the failure modes are similar to those obtained in the first loading. Figure 20 shows the similar P-Δ curves obtained under the first and second loadings.

The above tests show that the average maximum load capacity of the two-layer scaffolds with top screw jacks extended in the first loading is 841.027 kN, and the average corresponding vertical deformation is 22.391 mm. The average maximum load capacity in the second loading is 561.087 kN, and the average corresponding vertical deformation is 20.424 mm. The load capacity of the scaffolds in the second loading is 67% (=561.087/841.027) of that in the first loading.

Comparing with the average maximum load capacity of the two-layer basic setup scaffolds (907.346 kN), the average maximum load capacity of the two-layer scaffolds with top screw jacks extended (841.027 kN) is 93% (=841.027/907.346) of that of the basic setup. This implies that extending the top screw jacks of isolated heavy-duty scaffolds to 75 cm has a negligible effect on the load capacity of the isolated heavy-duty scaffolds.

4.6 Extension of Both Top and Base Screw Jacks

For the five tests in this case (A, B, C, D and E), the maximum load capacities under the first loading are 813.937 kN, 878.900 kN, 963.234 kN, 672.834 kN and 849.996 kN, respectively, and the corresponding vertical deformations are 21.700 mm, 21.538 mm, 23.663 mm, 20.006 mm and 21.750 mm. Table 1 shows the test results.

Figure 22 shows the P-Δ curves obtained in test A of scaffolds with both top and base screw jacks extended under the first and second loadings. The curve for the first loading shows that the correlation between load and deformation increases linearly after loading. When the load increases to the maximum value of 813.937 kN, vertical deformation is 21.700 mm. The failure mode shows that the deformations occur at the connection joints between the top/base screw jacks and the vertical members of the scaffolds. The deformation of the scaffolds unit is comparatively smaller than that of two screw jacks.Figure 23 shows the failure mode of the scaffolds.

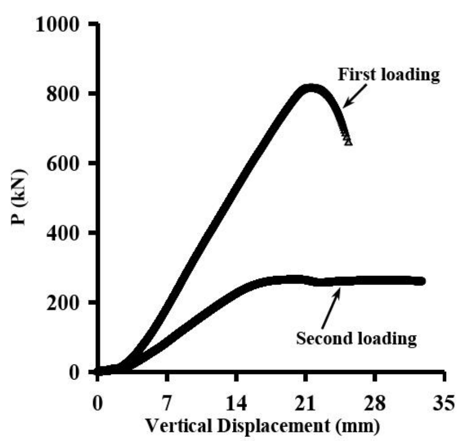


Figure 22. P-Δ Curves of Two-layer Setup with Extensions of Both Top and Base Screw Jacks under the First and Second Loadings in Test A

Figure 23. Failure Mode of Two-layer Setup with Extensions of Both Top and Base Screw Jacks

The maximum load capacities of second loading of groups A, B, C, D and E tests are 266.141 kN, 365.079 kN, 212.806 kN, 370.881 kN and 298.410 kN, respectively, and the corresponding vertical deformations are 20.125 mm, 22.000 mm, 28.913 mm, 15.537 mm and 18.881 mm. The failure modes observed under the second loading generally resemble those under the first loading. However, Figure 22 shows that the P-Δ curve under the second loading differs from that under the first one. Because the deformation of the scaffolds after the first loading was comparatively more obvious, this led to a bigger initial imperfection of the scaffolds under the second loading than that of other test configurations.

The above tests of the two-layer scaffolds with both top and base screw jacks extended showed that average maximum load capacity in the first loading is 835.780 kN and that the average corresponding vertical deformation is 21.731 mm. The average maximum load capacity in the second loading is 302.663 kN, and the average corresponding vertical deformation is 21.091 mm. The load capacity of the scaffolds in the second loading is 36% (=302.663/835.780) of the load capacity in the first loading. As shown above, the decrease of the load capacity is substantial. This is due to that serious deformations occur at the connecting joints between the top/base screw jacks and the vertical members of the scaffolds, which led to serious inclination of the scaffolds before being put under the second loading (Figure 24).

The comparisons showed that the average maximum load capacity in two-layer scaffolds with both top and base screw jacks extended (835.780 kN) is 92% (=835.780/907.346) of that in two-layer basic setup scaffolds (907.346 kN). The extension of both the top and base screw jacks seems to have a negligible effect on the load capacity of isolated heavy-duty scaffolds.

However, comparison between the poorer load capacity obtained in test D (672.834 kN) and the average maximum load capacity of the two-layer basic setup scaffolds (907.346 kN) shows that the load capacity of test D approximates 74% (=672.834/907.346) that of the basic setup, which represents a 26% decrease in the load capacity of the basic setup. In addition, the failure modes revealed deformations at the connecting joints between the top/base screw jacks and the vertical members of the scaffolds. This failure style is different from that of other scaffold setups, of which the deformations usually occur on the scaffolds unit. Scaffold setups with both top and base screw jacks extended should be used cautiously in construction sites.

Figure 24. Failure at Connecting Joints between Top Screw Jacks and Vertical Members Observed in Test of Extension of Both Top and Base Screw Jacks

4.7 Steel Tube Shores without Enclosed Restraint on Top of Scaffolds

Under the first loading, tests A and B in this case revealed the maximum load capacities of 231.210 kN and 234.283 kN, respectively, and the corresponding vertical deformations of 47.689 mm and 45.114 mm. Table 1 shows the test results.

Figure 25 shows the P-Δ curve obtained in test A of the two-layer isolated heavy-duty scaffolds reinforced with steel tube shores without an enclosed restraint on the top. The curve in the figure shows that the load and deformation relationship increases linearly after loading. When the load is increased to 113.659 kN, an up-and-down movement of the curve results from a tilt in the four steel tube shores on top of the isolated heavy-duty scaffolds. The maximum load capacity of the two-layer isolated heavy-duty scaffolds is 231.211 kN, and the corresponding vertical deformation is 47.689 mm.

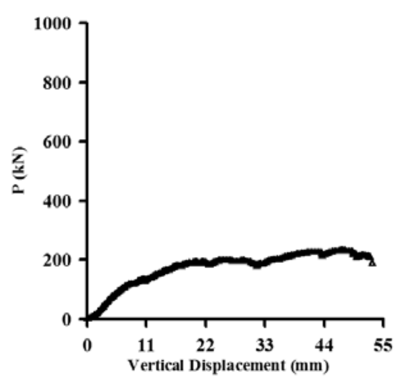


Figure 25. P-Δ Curve of Two-layer Setup Reinforced with Steel Tube Shores without Enclosed Restraint on the Top in Test A

The test configuration with steel tube shores added without an enclosed restraint on top of the isolated heavy-duty scaffolds is a combined setup involving two different materials, which is unlike the setups mentioned above. When failure occurred, the steel tube shores without enclosed restraint on top of the scaffolds became tilted. During loading, both ends of the top steel tube shores were somewhat damaged by the simple style screw jacks. The deformation of the isolated heavy-duty scaffold unit was comparatively less than that of steel tube shores. Figure 26 shows the failure mode of the scaffolds. Similar failure modes were observed in tests A and B. The extreme failure of the 4 steel tube shores on the upper layer precluded readjustment and restoration of the original position of the scaffolds. Therefore, the second loading was not performed.

The above tests of two-layer scaffolds reinforced with steel tube shores without enclosed restraint showed an average maximum load capacity of 232.747 kN and an average corresponding vertical deformation of 46.402 mm. The average maximum load capacity in the two-layer scaffolds reinforced with steel tube shores without enclosed restraint on the top (232.747 kN) is 26%(=232.747/907.346) of that in the two-layer basic setup scaffolds (907.346 kN). The load capacity decreases by 74%.Further comparisons showed that the average maximum load capacity of the two-layer scaffolds reinforced with steel tube shores without enclosed restraint on the top (232.747 kN) was only 28% (=232.747/841.617) of that of two-layer heavy-duty scaffolds with top screw jacks extended (841.027 kN). This result shows that when steel tube shores without enclosed restraint are added on top of the isolated heavy-duty scaffolds, the load capacity of the scaffold system will be seriously reduced.

Figure 26. Failure Mode of Two-layer Setup Reinforced with Steel Tube Shores without Enclosed Restraint

4.8 Steel Tube Shores with Enclosed Restraint on Top of Scaffolds

In the two tests in this case (A and B), the maximum load capacities obtained under the first loading are 220.610 kN and 207.607 kN, respectively, and the corresponding vertical deformations are 23.836 mm and 28.651 mm. Table 1 shows the test results.

Figure 27 shows the P-Δ curve obtained in test A of two-layer isolated heavy-duty scaffolds reinforced with steel tube shores with enclosed restraint on the top. When failure occurred, the maximum load was 220.610 kN, and the corresponding vertical deformation was 23.836 mm. Additionally, the four steel tube shores on the top of the isolated heavy-duty scaffolds tilted simultaneously, and both ends of these top steel tube shores were somewhat damaged by the simple style screw jacks. The deformation was less severe in the isolated heavy-duty scaffolds than in the steel tube shores. Figure 28 shows the failure mode of the scaffolds.

In the two-layer scaffolds reinforced with steel tube shores with enclosed restraint on the top, this study shows that the average maximum load capacity is 214.10 kN and the average corresponding vertical deformation is 26.244 mm. Comparing with the average maximum load capacity of the two-layer heavy-duty scaffolds with top screw jacks extended (841.027 kN), the average maximum load capacity of the two-layer scaffolds reinforced with steel tube shores with enclosed restraint on the top is 25%(=214.108/841.617) of that of the scaffolds with top screw jacks extended. This result shows that the load capacity of the scaffolds reinforced with steel tube shores *with* enclosed restraint is slightly lower than that of the scaffolds reinforced with steel tube shores *without* enclosed restraint. Because one of the four steel tube shores is tilted, the other 3 shores are pulled together due to the enclosed restraint. Therefore, the load capacity of the scaffolds reinforced with four steel tube shores *with* enclosed restraint is slightly lower than that of the scaffolds reinforced with four steel tube shores *without* enclosed restraint.

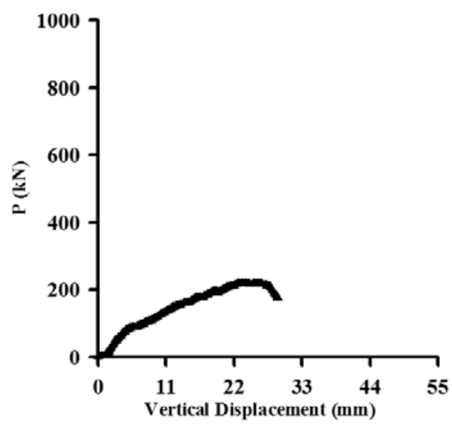


Figure 27. P-Δ Curve of Two-layer Setup Reinforced with Steel Tube Shores with Enclosed Restraint on the Top in Test A

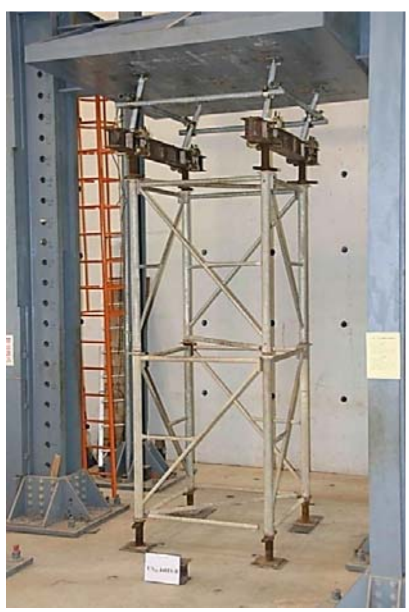


Figure 28. Failure Mode of Two-layer Setup Reinforced with Steel Tube Shores with Enclosed Restraint

5. COMPARISON OF CRITICAL LOADS OF ISOLATED HEAVY-DUTY SCAFFOLDS

5.1 Comparison of Different Scaffold Setups

The critical loads of various test configurations of the two-layer isolated heavy-duty scaffolds were compared based on that of the basic setup of two-layer isolated heavy-duty scaffolds. Figure 29 shows the comparison results. Comparison with the basic setup showed that the critical load of scaffolds with non-stiffness base screw jacks is 95% of that of scaffolds in the basic setup. Thus, the bending moment stiffness provided by the base screw jacks of the scaffolds is negligible.

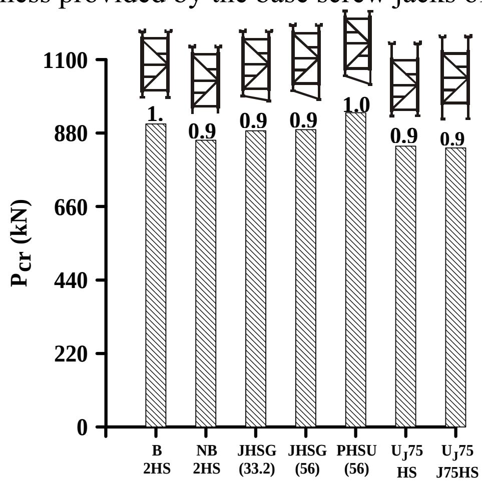


Figure 29. Comparison of Critical Loads of Isolated Heavy-duty Scaffolds in Various Configurations

The critical load of the scaffolds with 33.2 cm difference in ground elevation is 98% of that of scaffolds in the basic setup. The critical load of the scaffolds with 56 cm difference in ground elevation is also approximately 98% of that of scaffolds in the basic setup. Therefore, extending the base screw jacks of the scaffolds with difference in ground elevation on one side has a negligible effect on the critical load of the isolated heavy-duty scaffolds.

The comparisons showed that the critical load of scaffolds with 56 cm top difference in elevation is 104% of that of scaffolds in the basic setup. This difference is likely a result of test error. However, it is also the possible error that the scaffolding structure was put upside down to simulate the top difference in elevation of the scaffolds on the ground. Essentially, in scaffolds with top difference in elevation in this study, the extension of the top screw jacks on only one side has insignificant effect on the critical load of the isolated heavy-duty scaffolds.

The comparisons showed that the critical load of scaffolds with top screw jacks extended to 75 cm is 93% of that of scaffolds in the basic setup, and the critical load of the scaffolds with both top and base screw jacks extended to 75 cm is 92% of that in scaffolds in the basic setup. The test results for these configurations in this study show that extending the screw jacks of the scaffolds has a negligible effect on the critical load of isolated heavy-duty scaffolds.

However, when both top and base screw jacks of the scaffolds are extended to 75 cm, one test revealed only 74% of load capacity of the basic setup. As observed in failure mode, the deformation occurred at the connecting joints between the extended top/base screw jacks and the vertical members of the scaffolds. Therefore, contractors and designers must confirm the quality of the top and base screw jacks before applying this configuration.

5.2 Scaffolds with Different Top Shoring Configurations

Figure 30 shows the effect of different top steel tube shores configurations on scaffold load capacity. As shown in the comparison in the previous section, the test value of the scaffolds with top screw jacks extended to 75 cm approximated 93% that observed in the basic setup.

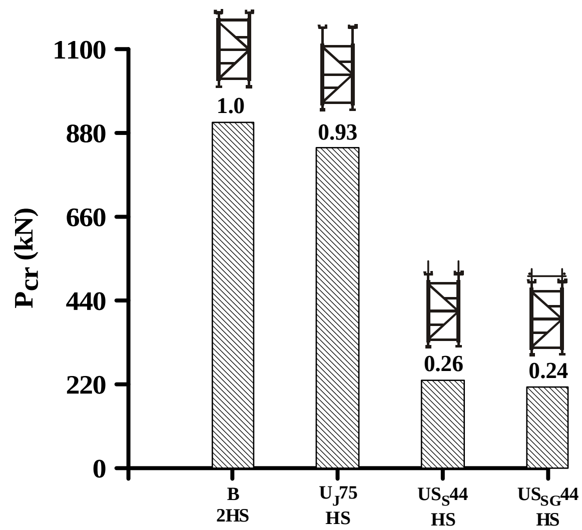


Figure 30. Comparison of Load Capacities of Isolated Heavy-duty Scaffolds in Different Top Steel Tube Shores Configurations

The test value of the isolated heavy-duty scaffolds with four steel tube shores (44 cm) *without* enclosed restraint on the top approximated 26% of that of the basic setup scaffolds. The test value of the isolated heavy-duty scaffolds with four steel tube shores (44 cm) *with* enclosed restraint on the top approximated 24% of that of the basic setup scaffolds. As indicated above, four steel tube shores (44 cm) added to the top of the isolated heavy-duty scaffolds substantially affected the load capacity of the isolated heavy-duty scaffolds.

In the case of four steel tube shores with enclosed restraint added to the top of isolated heavy-duty scaffolds, the failure of any one of the four steel tube shores under loading affected the other three shores. Since this phenomenon causes the failure of the entire scaffolding structure, it reduces the load capacity of the isolated heavy-duty scaffolds. Therefore, when using combined scaffold setups on construction sites, reinforcing the four steel tube shores with horizontal enclosed restraints is not advised.

As shown in the tests of the scaffolds with various top shoring configurations in Figure 30, the scaffolds with extended top screw jacks had the highest load capacity. Therefore, if the height of the isolated heavy-duty scaffolds must be extended, simply extending the top screw jacks is better than using the combined setup by adding steel tube shores on top of the scaffolds, which is usually used in the construction sites. Although extension of the top screw jacks reduces the risk of collapse of isolated heavy-duty scaffolds, excessive elongation of top screw jacks can cause a local failure of the screw jacks.

In addition, Table 1 shows that the vertical deformations of various setups of isolated heavy duty scaffolds were about 2 cm when the failure loads reached. The vertical deformation increases when the stories of the isolated heavy duty scaffolds are added. This vertical deformation needs to be considered especially during grouting concrete when the precision of the beams and slabs is required.

6. LOWER STRENGTH BOUND OF REUSABLE SCAFFOLDS

After observing the results of the first loading in the above tests, the scaffolds were unloaded, readjusted and put under the second loading. The test results for the second loading were considered the lower strength bound of reusable scaffolds. The strength reduction in the reusable isolated heavy-duty scaffolds was calculated by dividing the maximum load capacity of the second loading by that of the first loading is (Table 2).

Figure 31 shows the distribution of 1- to 3-fold standard deviations in the load capacity of reusable isolated heavy-duty scaffolds. The mean value of the reduction factor μ is 0.629, and the standard deviation σ is 0.113. Considering the lower limit of the load capacity, the reduction factor 0.516 is obtained by subtracting a 1-fold standard deviation from the mean value of reusable scaffolds (μ-σ). The reduction factor 0.403 is obtained by subtracting a 2-fold standard deviation (μ-2σ), and the reduction factor 0.29 is obtained by subtracting a 3-fold standard deviation (μ-3σ). When using the reusable isolated heavy-duty scaffolds to assemble temporary structures, the designers may choose an appropriate reduction factor to obtain a structural design consistent with the safety requirement.

Table 2. Ratios of Various Lower Strength Bounds of Reusable Isolated Heavy-duty Scaffolds

Type	Difference in elevation	Test group	Average values (kN) 1st loading, capacity	Average values (kN) 2nd loading, capacity	2nd loading/ 1st loading	Average value	Standard deviation
Two-layer basic setup	△h =0	A	894.003	288.316	0.323	0.629	0.113
		B	920.688	653.534	0.710		
Two-layer basic setup with non-stiffened base screw jacks	△h =0	A	762.584	382.272	0.501		
		B	912.560	577.229	0.633		
		C	899.974	623.155	0.692		
Difference in ground elevation	△h =33.2	A	911.671	515.991	0.566		
		B	862.262	539.247	0.625		
	△h =56	A	875.120	565.270	0.646		
		B	905.383	720.106	0.795		
Top difference in elevation	△h =56	A	998.337	720.458	0.722		
		B	883.406	496.046	0.562		
Extension of top screw jacks	△h =0	A	912.533	613.863	0.673		
		B	846.912	530.194	0.626		
		C	780.047	490.530	0.629		
		D	824.617	609.762	0.739		

Notes:
Average value: $\bar{x} = \sum_{i=1}^{n} x_i / n$; Standard deviation: $\sigma = \sqrt{\frac{\sum (x-\bar{x})^2}{(n-1)}}$

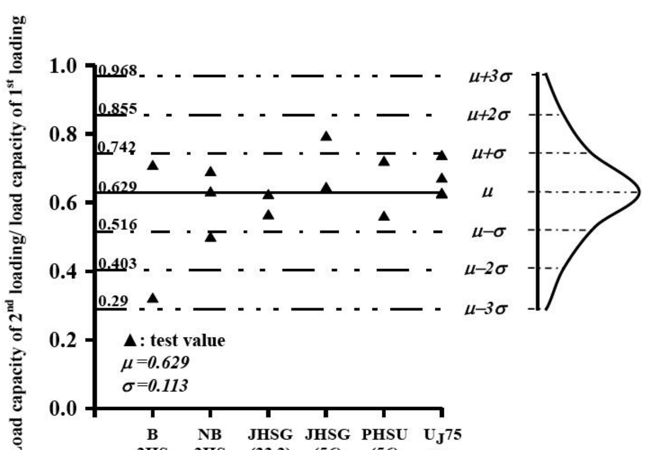


Figure 31. Distribution of 1- to 3-fold Standard Deviations in Load Capacities of Various Reusable Isolated Heavy-duty Scaffolds

7. CONCLUSIONS

The isolated heavy-duty scaffolds, which have high load capacity, are often used as the falsework during the construction stage of structures with high clearance, large spans and thick slabs, such as factory buildings, warehouses or gymnasiums. This study explores the critical loads and failure modes of isolated heavy-duty scaffolds in various setups by testing these scaffold configurations actually used on construction sites. The results of the tests are summarized as follows.

Since the bending moment stiffness provided by the base screw jacks of isolated heavy-duty scaffolds is negligible, the base has limited effect on the overall load capacity of isolated heavy-duty scaffolds. When isolated heavy-duty scaffolds are set up on ground with varying elevation or under an inclined top slab with varying elevation, their load capacity is not substantially affected as long as the difference in elevation is less than 56 cm. In a modular structure, the total height of multiple-layer isolated heavy-duty scaffolds is often insufficient to reach the interior ceiling of a construction structure, which leaves a gap between the top of the scaffolds and the slab of the construction structure. On construction sites, the gap is typically filled by adding steel tube shores on the top of the isolated heavy-duty scaffolds. However, the load capacity of the combined scaffolding structure is only 30% of that of the isolated heavy-duty scaffolds. In other words, this combined setup causes about 70% reductions in the load capacity of these scaffolds. Instead of the combined scaffolding structure, it is advisable to directly extend the top screw jacks of the isolated heavy-duty scaffolds to fill the gap between the top of the scaffolds and the slab. The load capacity of isolated heavy-duty scaffolds assembled from a single material is much higher than that of the scaffolds composed of other materials. For the strength design of the reusable isolated heavy-duty scaffolds, the reduction factors presented in this study can be used as reference. Designers can consider appropriate reduction factors to design reusable isolated heavy-duty scaffolds with various setups based on construction safety considerations. The vertical deformation of the isolated heavy duty scaffolding systems in tests of this study is about 2 cm. The value of the vertical deformation can be considered an index to evaluate the displacement of the beams and slabs after grouting concrete.

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