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# LOAD-CARRYING CAPACITIES OF SYSTEM SCAFFOLD STRUCTURES WITH DIFFERENT TYPES OF BRACING

CHI-LING PAN and CHIH-PENG YU

*Dept of Construction Engineering, Chaoyang University of Technology, Taichung, Taiwan*

This research focuses on the loading capacity of scaffolds with different types of bracing. The scaffolds without bracing and with four kinds of bracing were included in the test program. The material test and member test were first conducted in this study to obtain the material properties and the connection parameters for comparison. It was observed that the ultimate tested loads of specimens with bracing are much greater than those of the specimens without. Discussion turned to ultimate load, critical buckling load, and failure mode for all specimens based on the test results. In addition, software SAP2000 was used to predict scaffold strength. It was found that the discrepancy between ultimate strengths for scaffolds with and without bracings is limited because only vertical loads were applied to specimens. The predictions of ultimate strength became different for the scaffolds with and without bracings as long as the notional horizontal forces, which were used to simulate the initial imperfection, were applied on the scaffolds. Despite the expectation that the four bracing types would yield distinguishable results, the SAP2000-computed ultimate strengths for the bracings were quite similar. Therefore, a more realistic model was adopted to investigate the strength by including effects due to both $2^{nd}$-order geometric and simple material nonlinearity.

*Keywords*: Compression test, Ultimate load, Bracing, Model, SAP2000.

## 1 INTRODUCTION

Modular scaffolds are used as supporting scaffolds in construction sites. Compared to the frame-type steel scaffold, the system steel scaffold is more commonly adopted in the false work because it creates more working space, is fast to install and erect, and has a jack base that is easy to adjust. Peng et al. (2009) investigated the structural behavior and bearing capacity of system scaffolds. The research showed that when the number of scaffold stories increases, the critical loads of system scaffolds decrease. Diagonal braces markedly enhance the critical load of system scaffolds. In Peng's research, the effect of various diagonal brace positions on the critical load of a system scaffold was also examined and discussed. The analytical model was based on a 2-story system scaffold with four diagonal braces added to each story. The critical loads were markedly increased when diagonal braces were added to the structure. Figure 1 illustrates three configurations for the system scaffolds. Peng pointed out Case B had the highest critical load in these three Cases.

Weesner and Jones (2001) conducted load tests on four different types of frame scaffolding systems assembled to form a framework approximately 5m tall. The commercial software was also used to predict the ultimate load-carrying capacity of each system using both an eigen-buckling and a geometrically-nonlinear analysis. A three-dimensional model was built in ANSYS for each of the four frame types. In the comparison between the predicted and measured ultimate loads in four different scaffolding frames, Weesner and Jones concluded that the commercial software does indeed provide a reasonable upper bound prediction of ultimate capacity.

Yu et al. (2004) conducted a systematic study on the structural behavior of multi-story door-type modular steel scaffolds through both experimental and numerical investigations. Three one-story and three two-story modular steel scaffolds were built and tested to failure in order to examine the structural behavior of typical multi-story door-type modular steel scaffolds. In their study, a non-linear finite element model with high performance beam-column elements was established to evaluate the load carrying capacities of these scaffolds under idealized boundary conditions. Yu et al found the load carrying capacities of multi-story modular steel scaffolds to be very sensitive to the positional restraint, $k_p$, and the rotational restraint, $k_p$, provided at the top and the bottom of the scaffolds respectively. It is important to incorporate the effects of these restraints in assessing the structural behavior of the scaffolds under both experimental and numerical investigations. They also pointed out that cross-bracings are very important to the structural behavior of modular steel scaffolds as they can effectively reduce the effective lengths of the column members.

Both experimental and analytical studies were conducted in this research. The scaffolds with or without four kinds of bracing were included in the test program. A discussion was made for the ultimate load, critical buckling load, and failure mode for all specimens based on the test results. In addition, the commercial software SAP2000 was used to predict the strength of scaffolds. In addition, a more realistic model was also adopted to investigate the strength by including effects due to both $2^{nd}$-order geometric and simple material nonlinearity.

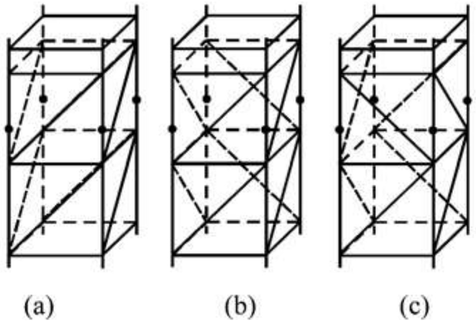
(a) (b) (c)

Figure 1. Different bracing installations (a) Case A; (b) Case B; (c) Case C.

## 2 EXPERIMENTAL STUDY

Three test programs were conducted in this research: (1) tests of two-story system scaffolds with different types of bracing, (2) tests of material properties for steel, and (3) tests of stiffness for joint connection. The MTS testing system shown in Figure 2 was used to conduct the material and stiffness tests. A 135-ton compression testing machine was used to test the system scaffolds, as can be seen in Figure 3.

## 2.1 Specimens

The system steel scaffold was assembled by three kinds of component: vertical prop, horizontal bar, and diagonal brace. A octagon steel plate with pre-fabricated holes was welded onto the vertical prop. Horizontal bars and diagonal braces were then lodged into these holes. For all test specimens, the nominal diameters of vertical prop, horizontal bar, and diagonal brace were 48.0 mm, 42.0 mm, and 33.4 mm, respectively. The length of vertical prop and horizontal bar were 180 cm and 180 cm, respectively, and the length of diagonal brace was designed to fit the diagonal length. In addition, the jack bases were placed on the top and bottom scaffold specimens.

Figure 2. MTS testing system.

Figure 3. Compression testing machine.

## 2.2 Test Setup

The height of scaffold specimens was about 419 cm. In total, two test specimens without installation of diagonal braces and eight test specimens with four types of bracing—Case A, Case B, Case C, and Case D—were tested and discussed in this study. The configurations of test specimens with diagonal braces are shown in Figure 4 to Figure 7. In order to observe and compare the bracing types, the scaffolds were opened up as presented in these figures. The letters, N, W, S, and E shown in these figures represent four sides (four directions) of specimen. In the designation of specimens, the first group number, 2L, represents a two-story system scaffold; the second letter with two numbers, D48, represents the diameter of vertical prop; and the third letter represents the bracing type. In addition, the vertical loads and displacements have been recorded, the LVDTs were placed and arranged to obtain the lateral movements, and the strain gauges were also mounted on some of specimens to measure the strain variations during the test.

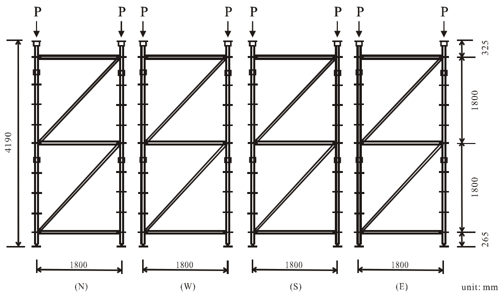

Figure 4. Case A diagonal bracing (2L-D48A).

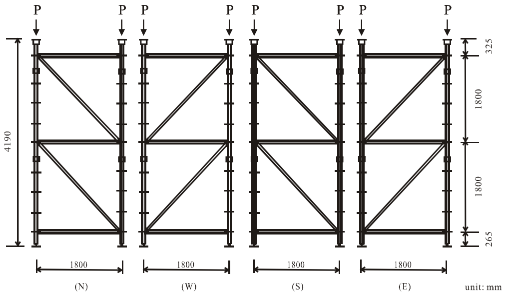

Figure 5. Case B diagonal bracing (2L-D48B).

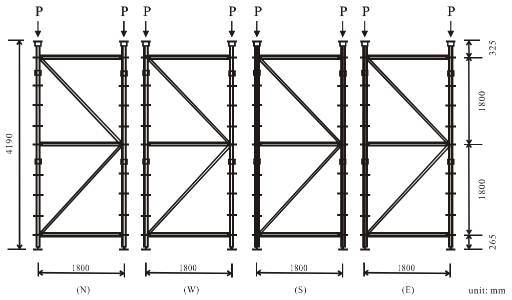

Figure 6. Case C diagonal bracing (2L-D48C).

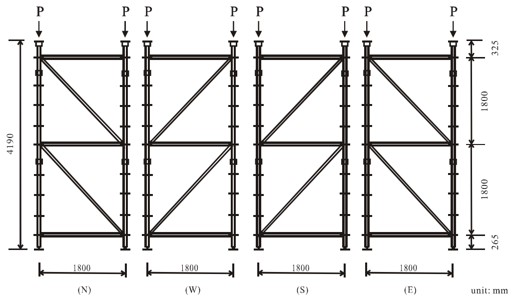

Figure 7. Case D diagonal bracing (2L-D48D).

## 3 EVALUATION OF EXPERIMENTAL DATA

Taking into account the cold-work effect, the material properties of the steel scaffold were obtained by using short-column test. The length of column was trimmed to be longer than 3 times diameter of steel tube, and shorter than 20 times of least radius of gyration to prevent the column from overall buckling. Based on the compressive testing, the material properties of D48, D42, and D33 scaffolds had $F_y$ values of 541.13 MPa, 460.77 MPa, and 341.98 MPa, respectively.

Based on the experimental results, three different types of failure were observed in the test specimens: (1) **Overall S-shaped buckling**. This kind of failure type was observed in most test scaffolds with diagonal braces. Figure 8 shows the photo of failure for the specimen 2L-D48A-2; (2) **Individual prop buckling**. The accuracy of scaffold assembly is very important. If the compression loads were not equally applied on the four vertical props, the prop would buckle earlier than other props, and the whole scaffold would not perform regularly; (3) **Overall single-curvature buckling**. It was found that only the test scaffolds without diagonal braces had this type of failure, as can be seen in Figure 9.

Table 1 lists the ultimate strength, the displacement at ultimate strength, and failure mode for each specimen. Based on the test results, it can be seen that the ultimate strength of scaffolds without installing diagonal braces has much lower values than those of scaffolds with diagonal braces. As for comparing the average ultimate strength of scaffolds with diagonal braces, the specimen with Case D bracing has the greatest value, the specimen with Case C bracing has the second-highest, and the specimen with Case A bracing has the smallest value.

Figure 8. Failure of Spec. 2L-D48A-2.

Figure 9. Failure of Spec. 2L-D48N-1.

Table 1. Ultimate strengths and displacements of test scaffolds.

| **Bracing type** | **Specimen no.** | **$P_u$ (kgf)** | **$D_u$ (mm)** | **Failure mode** |
|---|---|---|---|---|
| Case A | 2L-D48A-1 | 33463 | 17.538 | type (1) |
| Case A | 2L-D48A-2 | 32823 | 16.667 | type (1) |
| Case B | 2L-D48B-1 | 35138 | 23.725 | type (1) |
| Case B | 2L-D48B-2 | 32504 | 17.204 | type (2) |
| Case C | 2L-D48C-1 | 37234 | 20.275 | type (1) |
| Case C | 2L-D48C-2 | 32128 | 14.258 | type (2) |
| Case C | 2L-D48C-3 | 37167 | 18.825 | type (1) |
| Case D | 2L-D48D-1 | 38043 | 16.263 | type (1) |
| Case D | 2L-D48D-2 | 38755 | 17.825 | type (1) |
| Case N | 2L-D48N-1 | 10901 | 12.394 | type (3) |

## 4 VERIFICATION BY NUMERICAL SIMULATIONS

To better interpret the experimental test data, both SAP2000 and Mastan2 programs were used to provide numerical results associated with specific scaffold systems. Both programs can simulate $1^{st}$ and $2^{nd}$ order responses of space frames undergoing either elastic or certain inelastic behaviors. In a typical buckling-load analysis, critical loads of a specific structural system can be directly recovered by performing an eigen-analysis process for the system matrices, or reasonably approximated by a proper step-by-step scheme that carries out the $2^{nd}$ order structural analysis.

In this study, the four scaffold systems were modelled as space frames under designated scenarios with various boundary and loading conditions. It is generally noted that the performance of individual specimen can be roughly verified by matching specific structural elements, i.e., connection springs, loading ratios, and local abnormal properties. By FEM numerical modeling, one can easily gain an insight into the minor discrepancies observed in the different bracing systems. For example, Table 2 summarizes elastic buckling loads predicted by FEM numerical simulation in which a space frame model was employed. The listed results are obtained by evenly applying vertical loads at the top of the four studs for two types of assumed boundary conditions, namely Top(pinned)-Bottom(pinned) and Top(pinned)-Bottom(fixed). When comparing the buckling loads before and after adding braces, it is clear that the four cases lead to similar ratios, while Case D shows the best bracing effect for both sets of boundary conditions. It is worth noting that the experimental data also indicate that Case D specimens yielded the highest buckling loads among all.

Table 2. Ratios of elastic buckling loads by four types of braced scaffolds (evenly loading from top).

| **Boundary Conditions** | **Bracing type** | **$P_u$** |
|---|---|---|
| Top(pinned)-Bottom(pinned) | Case N | $P_0$ |
| | Case A | 6.47 $P_0$ |
| | Case B | 6.45 $P_0$ |
| | Case C | 6.40 $P_0$ |
| | Case D | 6.58 $P_0$ |
| Top(pinned)-Bottom(fixed) | Case N | $P_{0F}$ |
| | Case A | 4.45 $P_{0F}$ |
| | Case B | 4.28 $P_{0F}$ |
| | Case C | 4.36 $P_{0F}$ |
| | Case D | 4.61 $P_{0F}$ |

## 5 CONCLUSIONS

A total of 10 scaffolds with and without diagonal braces were tested and investigated. It was observed that the ultimate tested loads of specimens with bracing are much greater than those of the specimens without. As for comparing the ultimate strength of scaffold with diagonal braces, the specimen with Case D bracing had the highest value. It coincides with analytical findings that indicate the scaffolds with Case D bracing have the greatest buckling load for both different boundary conditions. In the analysis of system scaffolds, the notation of lateral forces, assumed to be 0.3% of ultimate load, was employed to simulate the initial imperfection of scaffold. It was found that the loading-carrying capacity decreased slightly as the lateral forces were applied for the scaffolds with diagonal braces. However, the value of ultimate strength was reduced dramatically for the scaffold without bracing.

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