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# EXPERIMENTAL STUDY ON ASEISMIC BEHAVIOUR OF THE REINFORCED CONCRETE FRAME-TRUSS STRUCTURE SYSTEM

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## ABSTRACT

This paper introduces a kind of structure system, reinforced concrete frame-truss structure system, which is means taking the reinforced concrete truss to subject the earthquake action. According to a large amount of the computing analysis and theoretical compression of the frame-truss structure with different kind of braces and storeys and experiments on the specimens of the frame-truss structural system, it has shown that the reinforced concrete frame-truss structure is about undifferentiated to resist the earthquake action, and the frame-truss structure has somewhat better property than frame-shear wall and frame structure.

## KEYWORDS

Earthquake engineering; Structure engineering; High-rise building; Frame-truss structure; Reinforced concrete truss structure; Pseudo dynamic testing; Reinforced concrete frame structure; Reinforced concrete frame-shear wall structure.

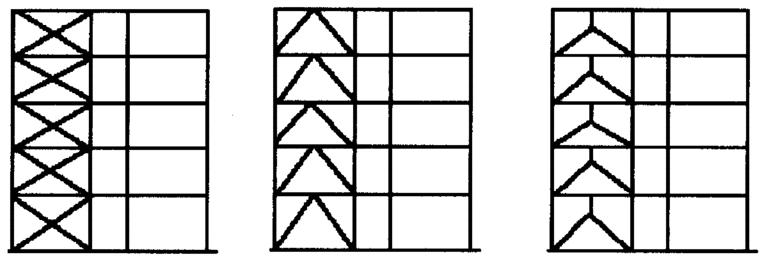
## INTRODUCTION

In generally, high-rise buildings are likely to use reinforced concrete frame-shear wall structural system, especially about 20 storeys. The frame-shear wall structure system has higher lateral rigidity and strength and, therefore, has good aseismic behaviour. The frame-shear wall structure system, as all we known, has some defects. (1) The lateral stiffness of the shear wall is much greater than that of frame structure, so that the deformation of the shear wall does not work in co-ordination with that of frame, and the bearing of coupling beams is not reasonable. It is difficulty to reinforce on the coupling beams at the section to link to the shear wall; In addition, a higher lateral rigidity would lead to a high seismic load on the structure because a stiffer structure tends to attract more seismic energy. Once shear wall failure, the structure would lose the resisting capacity of not only lateral force but also vertical static force.(2) Usually the shear wall structure need much material and is great in dead-weight, and bears much lateral force because great lateral stiffness, so that the foundation of the structure subjects to much load and is difficult to design; (3) the shear-wall structure is fragility if it damages under the action of a great lateral force, so the shear-wall structure is difficulty to control under the action of strong earthquake.

This paper suggested a kind of structure system; reinforced concrete frame-truss structure system. That means to use frame-truss to replace the shear wall of frame-shear wall structure. According to the results of the theoretical analysis and experiments to the frame-truss structure, the frame-truss structure is similar to frame-shear wall system in resisting lateral deformation, and surmounts the defects of the shear wall structure. It is possible to replace the shear-wall structure with frame-truss structure for the high-rise building of 10 to 20 stories.

## THE COMPRESSION ANALYSIS TO THE FRAME-TRUSS STRUCTURES WITH DIFFERENT KINDS OF BRACE

For understanding the earthquake resistant properties of the frame-truss structure and to compare the different kinds of frame-truss structure forms, it is essential to select optimally a structural form. Some of the frame-truss structures with three kinds of braces were computed (Den xiutai and Li tian,1994). Some of the frame-truss structures with different kind of brace form are shown in figure 1, which were computed in eight stories and sixteen stories. The truss with X brace as shown in figure 1a, called X form, is most used in steel structure and in reinforced concrete steel composite structure, but, usually, it is difficulty to put the doors and windows on the wall. The truss with K brace as shown in figure 1b, called K form, is not only to overcome the problems to open the doors and windows but also improving the beam. The truss with Y brace (upside down), called Y form, is succeed to the advantages of the K form, and is expected to the structure being ductility and the structure failure beginning at the braces. The frame structure and the shear wall structure with the same storey were computed as well.



(a) X form (b) K form (c) Y form

Figure 1. Three kinds of frame-truss structure

The frame truss structures were computed by the mode superposition method. After computed the effect of the earthquake, then added the effect of the dead load. The results computed were compared with that of the pure frame structures and the frame-shear wall structure. The self-vibration periods of the frame-truss structure and frame structure are shown in the table 1 and table 2.

Table 1. The Self-Vibration Periods of the Structure Computed (16 storeys)

| | F-T with X brace | F-T with K brace | F-T with Y brace | F-T |
|---|---|---|---|---|
| $\omega_1$(Hz) | 8.423 | 8.070 | 8.075 | 5.771 |
| $T_1$(s) | 0.7459 | 0.7786 | 0.7781 | 1.0887 |

Table 2. The self-vibration periods of the structure computed (8 storeys)

| | F-T with X brace | F-T with K brace | F-T with Y brace | F-S | S-W |
|---|---|---|---|---|---|
| $\omega_1$(Hz) | 22.398 | 21.888 | 20.270 | 8.440 | 19.299 |
| $T_1$(s) | 0.2805 | 0.2871 | 0.3100 | 0.7444 | 0.3256 |

F-T is frame-truss structure, F-S is frame structure, S-W is shear-wall structure

The internal force of the frame-truss structures were computed, from which we knew that the internal forces of the frame structure were much great than frame-truss structures and the frame truss structure with X form brace were the least of all.

Following conclusions from the compared results are derived: (1) for resisting the lateral deformation, the X form of the brace is similar to the K form of the brace, the lateral deformation of the frame-truss structure with Y (upside down) form of the brace is a little greater than other two kinds of brace (Figure 2), and the deformation of the frame structure is much greater than frame-truss structures; (2) the resistance ability to lateral deformation of the frame-truss structures is similar to that of the shear-wall structure; (3) the braces of the frame-truss structure with X and K form subject mainly to axial force, the moment is smaller, and the internal forces is smaller than other two kind of frame-truss structure. The internal forces of the frame structure are the greatest both in the columns and beams.

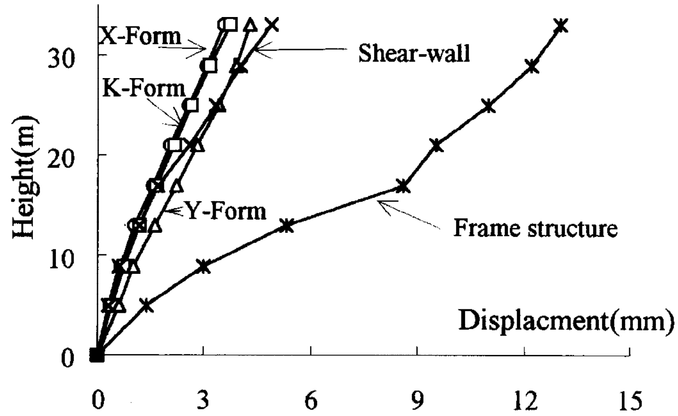


Figure 2. The displacements of the frame-truss structures, frame and shear wall structure

The above results document that the frame-truss structural system is good to resist earthquake action. It may be possible to replace the shear wall of the frame-shear wall structure with the truss. For examining the imagination, it is essential to study the elasto-plastic response under the strong earthquake action, and to understand the failure process of the frame-truss structure.

## EXPERIMENTAL STUDY

For the purpose of probing the earthquake resisting behaviour of frame-truss structure, two specimens were selected from about an 18 story building , which was the typical structure plane which commonly used in such as office buildings. The models are composed by two stories and three spans with scale 1:4. The specimens were designed on a general frame-shear wall structure first, then the part of the shear wall was replaced by the truss. Finally, the internal forces were computed, and the sections of the elements were designed. The specimen and measurements arranging were just as figure 3. The specimens were

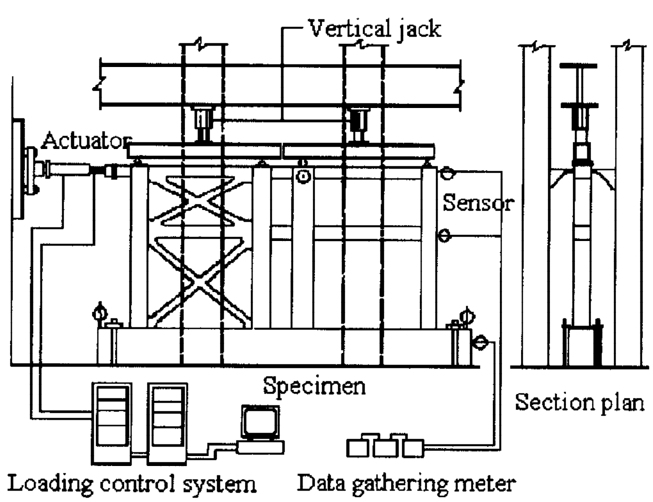


Figure 3. Configuration of testing apparatus and structural model

experimented on purso dynamic, taking the real earthquake recording data as inputting. The experiments were carried out step by step, according to the maximum value of earthquake accelerate.

To investigate the cracking and failure development of the frame-truss structure models completely, an on-line computer-controlled experimental procedure, so-called pseudo dynamic test method was chosen. The merit of this test method is that the response behaviour is preceded step by step directly using the measured restoring force from the test specimen. In this way, this is more reliable than in the other test method such as cycle test method. During the pseudo dynamic test, the specimen behaves as if it is subjected to an actual earthquake although time is largely lengthened as compared with the real earthquake. An advantage over the shaking table tests is that response behaviour and failure mode of the specimen can be observed in detail. Moreover, the pseudo dynamic test does not need such a large scale testing equipment or measuring devices as the shaking table test, and it can be applied to almost all kinds of structures regardless of their scales.

The earthquake waves used in the tests were choose from the EL Centro (1940.5. N-S), which was recorded on the middle hardpan, and the PASADENA (1952.7. E-W), which was recorded on the soft clay. The model structures were subjected to the earthquake scaled to the peak acceleration of 200 gals, 400 gals (500 gals), 800 gals, 1200 gals, 2400 gals, and 3400 gals. The input accelergram is show in figure 4.

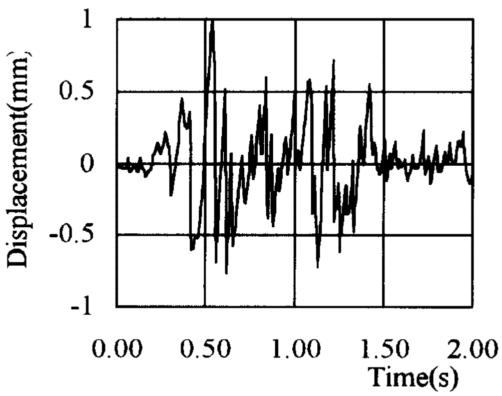



Figure 4a. EL-Centro (N-S)

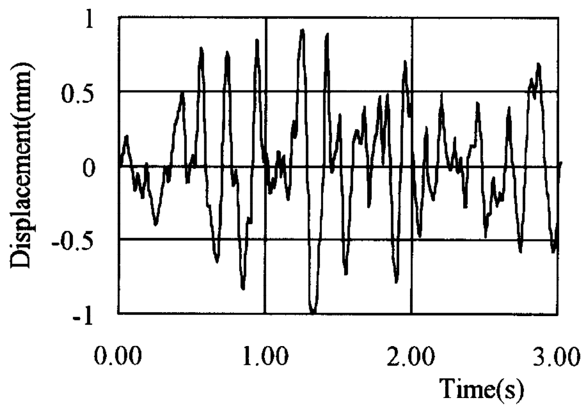



Fig.4b Pasadena (E-W)

Figure 4. Inputting accelergram.

## MAIN TEST RESULTS AND ANALYSIS

<u>The Deformation Characteristic</u>

The figure 5 shows the relationship of the lateral displacement to the lateral force between the loading point and the foundation, which is the pseudo dynamic test under the different input of the earthquake recording and each with different earthquake peak value. Clearly the shape of the relation curve is similar to that of general frame-shear wall structures.

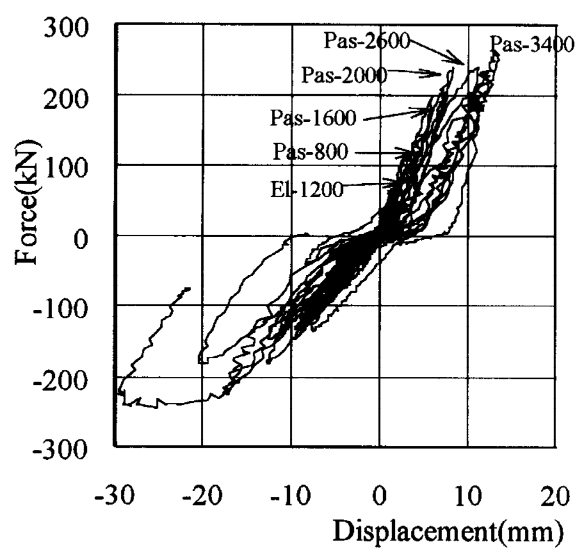



Figure 5. The relationship of P-Δ

Before the brace of the truss began yielding, when input the earthquake recording of PASADENA with the peak acceleration value 1600 gals, the deformation was smaller. After the maximum input acceleration value was great 1600 gals, the deformation of the model developed, the cracking on the braces increased, and the bars in the brace yielded. Accordingly, the elasticplastic property of the braces has greater influence on the aseismic property of the frame-truss, which the deformation of the structure is affected directly.

The Time History of the Specimens

The figure 5 shows the time history of the specimens experimented. Figure 5a is the structure just in cracking, figure 5b is the structure begin to yield and figure 5c is the structure nearly to failure. From figure 5 we can see that that is interested that the time of the maximum peak value changed along with the structure damage. At the beginning, the maximum peak value of the displacement happened at the beginning of the response and the peak values were about similar after the structure yielding, but the maximum peak value happened only after a long time response. From figure 5, we can known the aseismic property of the frame-truss structure transforming greatly.

The Failure Characteristic of the Specimens

In the processing of cracking development and failure of the frame-truss structure, the frame-truss structure under the action of the earthquake shows a character of multiple line of defence. Figure 7 gives the cracking developing process of the specimen at the different stages with different maximum peak value. The crack started to appear on the braces, when the peak value of the input acceleration was about 400-500 gals, as shown in figure 7a. As soon as the crack appearance, it breaks through the section, only a little crack is not through. This proves that the internal forces of the braces are mainly subject to axial force and the moments are smaller. And this is almost identical to the results computed.

The beams began crack along with the increase of the acceleration peak value of the input earthquake. First crack of the beam appeared on the part of the truss, then the beams of the frame part and the coupling beams as well. The crack's pattern of the beams presented in the flexure, but the coupling beams

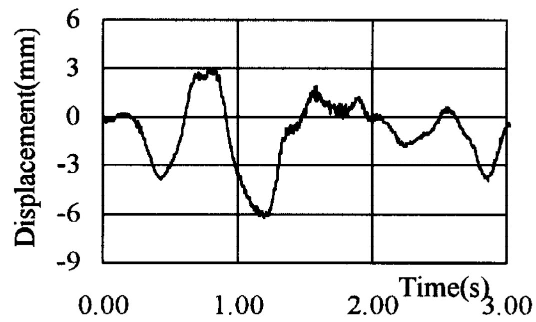



Figure 6a. Time history of displacement before yeilding

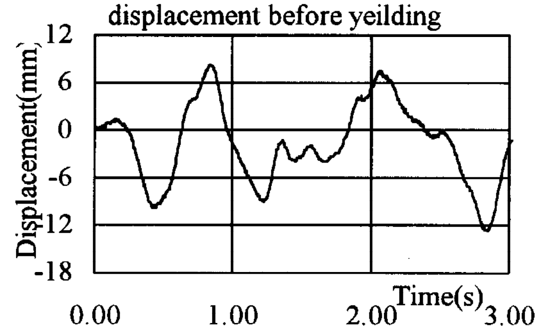
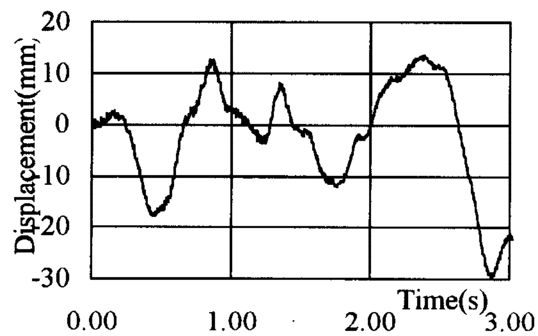
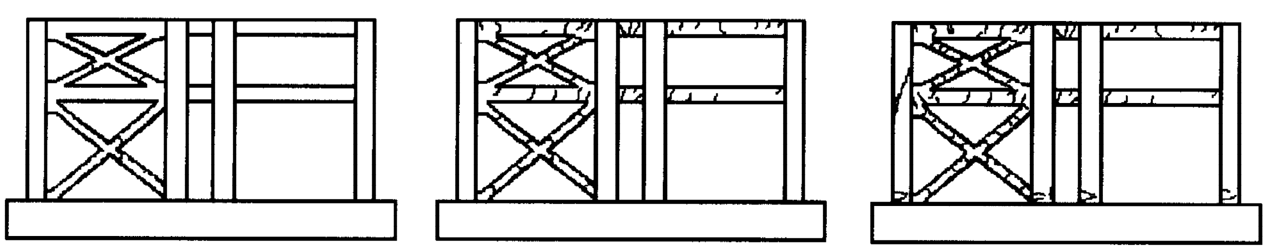



Figure 6b. Time history of displacement after yeilding




Fogure 6c. Time history of displacement near to fail



a. Beginning cracking b. Beginning Yielding c. Begging failing

Figure 7. The crack patterns of the frame-truss structure.

presented in the shear-bearing type first. With the increasing of the maximum peak value of the input earthquake, the bars in the brace yielded, then the crack of the braces increased evidently such as in the figure 7b. After the brace yielded, the crack on the brace increased slowly. On the beams, however, the crack added and spacing increased. When the peak acceleration reached 2000 gals, the compressed brace appeared the crushing sign, but this process developed slowly. The columns were not crack until the lateral deformation of the specimen was quite higher and the creaks on the braces and beams were plentiful. After the crack of the column appeared, the specimen was destroyed. The test ended at acceleration peak value of 3400 gals. The final failure pattern was shown in figure 7c.

From the mention above, the braces of the truss crack and failure first, which bear axial extension force and are easy to crack, then the beams of the truss crack. The columns of the structure crack lastly. Although the brace of the truss crack and failure first, it is hardly influence on the bearing capacity. Obviously, this kind of structure provides three lines of defence to resist the earthquake force. On the other hand, the earthquake force decreases along with the change of the structure character. Accordingly, a basic criterion of aseismic design is suggested to this kind of structural system. That is "strong column, middle beam, weak brace". The frame-truss structure, designed on that principle would not collapse suddenly under a strong earthquake action.

<u>The comparison of frame-truss with or without the frame</u>

One of the specimen, just as shown in figure 3, was tested in twice. When the brace of the truss began yield, the coupling beams were broken, and the part of truss only tested again for comparing the frame-truss structure with or without the part of frame. From the results of the test, the force response of the truss structure with or without the part of frame is nearly the same, only the displacement of the specimen without the part or frame was greater. the relation curves of the lateral force to displacement of the specimen with and without frame are given in figure 8. The specimen without the part of frame, however, was tested after the same specimen with frame, which had much crack developed.

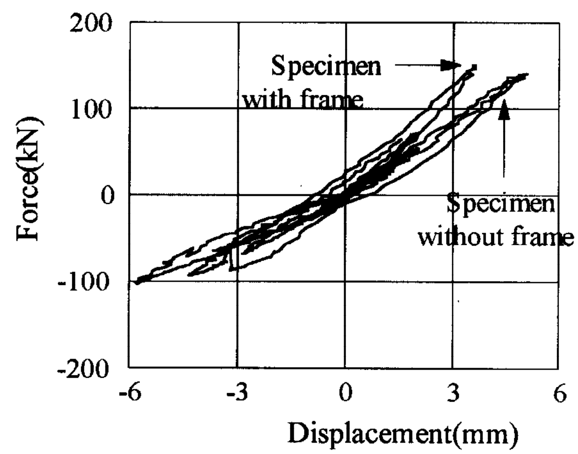



Figure 8. The relationship the truss structure with and without frame

<u>The Property of the Coupling Beams Improved</u>

The coupling beams in the frame-truss structure are usually the weak link and easy to fail in fragile. Although shear cracks started early, in this test, the coupling beams developed slowly. The shear cracks on the coupling beams do not expand to a certain extent until the column failed. These showed that the property of the coupling beams was improved in the frame-truss structure.

## CONCLUSIONS

According to the results of the computation and the experiments, the characters of the frame-truss structure are summered as followings,

(1) The lateral stiffness of frame-truss structure is much great than frame structure and is similar to frame-shear wall structure. The frame-truss structure with X brace or K brace is better to ascismic action.

(2) The process of cracking and destroying of the frame-truss structural system is beginning at the braces, then the beams, the column cracking and destroying only after the braces and beams cracking developed fully. So the aseismic essential principle of the frame-truss structural system we can get is 'strong column, middle beam and weak brace'.

(3) The frame-truss structure shown the characters of multiple line of defence, Before the braces are failed in tension or in compression, the earthquake force is mainly subjected by the truss. After the brace fails, the frame still keeps in a whole and dose not lost bearing capacity.

(4) The hysteresis characteristic of the reinforced concrete frame-truss structural system is similarly to that of the reinforced concrete frame-shear wall structural system.

(5) The failure of the coupling beams is much later after the brace cracking during the test, and the cracking of the coupling beams develops slowly, which show that the earthquake resistant behaviour of the frame-truss structural system is better than that of frame-shear wall structural system.

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