LATERAL LOAD-BEARING CAPACITY OF WOOD DIAPHRAGM IN HYBRID STRUCTURE WITH CONCRETE FRAME AND TIMBER FLOOR

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ABSTRACT: In this paper, a type of hybrid structure with concrete frame and timber floor system was studied. This hybrid structure got strength from two types of structures, and suited for multi-storey buildings. Based on the different in-plane stiffness assumption of the floor system, Sap2000 was used to set up four different hybrid structural models: detailed timber floor model, simplified timber floor model, rigid floor model and flexible floor model. And the four models were used to do numerical simulation for a test of a one storey hybrid structure under lateral load. Results showed that, light frame timber floor system could maintain a high in-plane stiffness and strength during the elastic and plastic range of the hybrid structure. Detailed timber floor model and simplified floor model could both do very good simulations of the hybrid structure and detailed floor model could be replaced by the simplified model. Compared to the flexible floor, the behaviour of the timber floor system in this hybrid structure was more close to the rigid floor.

KEYWORDS: hybrid structure, concrete frame, timber floor, monotonic load, cyclic load, finite element method

1 INTRODUCTION

Wood is renewable and environmental friendly building material, and timber houses are very popular in developed countries, such as North America, North European countries, USA and Japan. In last ten years, light frame wood buildings came into Chinese market and made certain approaches. However, pure wood structures are usually applied in low-rise residential buildings, which are not accordant with the situation of China with limited land but a large population [1].

In this background, a type of hybrid structure, combination of concrete frames and wood diaphragms, is raised. In this hybrid structure, reinforced concrete is used to build up the frames, providing resistance for horizontal and lateral forces, while wood diaphragms are used for floor system. This kind of structure could be applied in multi-story buildings. Due to the lightness of the wood diaphragm, the dead load and lateral seismic load are maximally lowered. But at the same time, questions come out, how the wood diaphragm and concrete frames work together under lateral load.

In Chinese design code for concrete structure, wood floor is recognized as "flexible floor", which means wood floor has no in-plane stiffness and when earthquake comes, the lateral forces would be distributed in concrete columns by how much the horizontal load each column takes [2]. But in fact, a well constructed wood diaphragm has a certain high in plane stiffness and might be able to transfer lateral load between concrete columns.

In order to get a better understanding of in-plane behaviour of the wood diaphragm, previous in-plane testing of wood diaphragms are reviewed. Some of the review works were done by Bott et al (2001) [3]. Early in-plane tests of plywood-sheathed were performed by Countryman (1952) [4]. Specimens were tested under monotonic load. Through the test, it was found that, shear deformation, as opposed to flexural deformation, was determined to be the predominant form of deformation. Diaphragm behave like a deep horizontal girder, cord members behave like flanges to resist the flexural tension and compression stresses, while the sheathing panel acts like a web to resist the shear forces. The strength and the stiffness of the specimens depended primarily on the strength of the sheathing-to-frame nailed connections. Stillinger and Countryman (1953) tested roof diaphragms constructed with the lightest framing and plywood thickness permissible at that time for a roof of this size. It was found that light weight framing system performed adequately enough to be adopted in construction practise. Also, for unblocked diaphragms, no special boundary nailing detail was required [5]. Tissell (1966) tested 19 full-scale
diaphragms, with varied plywood characteristics, sheathing-to-framing connections, nail types, and framing member types, under monotonic load [6]. The design shear values were found to be much higher than the ultimate shear capacity got from tests. Effects from plywood grade and quality were found to be negligible. It was also found that shorter ring-shank nails could also be used as long as a minimum penetration is attained.

On the other hand, the dynamic characteristics of wood diaphragm were studied in a few tests. Polensek (1979) tested plywood sheathed diaphragms to fetch their damping characteristics. The results of these dynamic tests yielded average equivalent viscous damping ratios between 7% and 11% critical [7]. Jewell (1981) did some test on partial diaphragms in order to study the effects of different parameters, such as nail spacing, boundary conditions, connection details, and load types on the in-plane stiffness and damping characteristics of wood diaphragms [8]. In order to determine the local and global in-plane shear stiffness to variations of blocking, openings, plywood thickness, corner stiffeners and framing nail sizes, Corda (1982) tested six wood diaphragms to failure under cyclic load. Nail yielding on the diaphragms decreased the in-plane stiffness. Increased plywood thickness (without using longer nails) and corner openings reduced strength but had little effect on stiffness [9]. Tissell and Elliott (1997) performed diaphragm testing for high-load conditions equivalent to earthquake excitations [10]. The main purpose was to give suggestions to the design and construction approaches for “high-load” diaphragms, which may incorporate two layers of plywood, thicker plywood, or stronger fastener conditions. Results showed that it was possible to increase the shear strength by increasing the number of fasteners. Staples were quite enough in stead of nailed sheathing-to-framing connections. Field glued joints and a reduced number of nails were found to be adequate. Filiatrault and Fischer (2002) did in situ quasi-static tests on a full-scale wood diaphragm in two-storey wood frame house to investigate the in-plane rigidity of the diaphragm [11]. Parameters, such as the nail schedule, panel-edge blocking, sub-floor adhesive, perpendicular walls above and below the diaphragm and wall finish materials, were considered. It was found that panel-edge blocking caused a certain increase of the diaphragm shear stiffness. Also, the presence of perpendicular walls acting as chord members caused a significant increase of in-plane rigidity of the diaphragm. Peralta and Bracci (2004) tested the in-plane behaviour of pre-1950s existing and rehabilitated wood floor and roof diaphragms in unreinforced masonry buildings [12]. Specimens were constructed with element and connections which were typical of pre-1950s and tested, retrofitted and retested again using different rehabilitation methods, including enhanced shear connectors and perimeter strapping, steel truss attached to the bottom of the joists and connected to the vertical lateral forces resisting system. Reversed cyclic loading were applied to the specimens to evaluate their in-plane deformation performance, which were used to develop backbone curves. These backbone curves provided the basis for bilinear curves that define yield strength and displacement, effective stiffness and post-yield stiffness. And the results were compared with the provisions for the wood diaphragms in the FEMA guidelines for seismic rehabilitation of buildings.

The experimental programs listed above have provided very useful information on the in-plan behaviour of wood diaphragms, however, the performance of wood diaphragms in the hybrid structure under lateral load was still need to be studied.

In order to study the behaviour of concrete-wood hybrid structure under lateral load, a test was done in national key laboratory of disaster reduction of Tongji University in January, 2008. In this test, a one storey concrete frame with wood diaphragm on top was constructed and tested under monotonic lateral load in elastic range and cyclic lateral load to failure. The data was recorded and analyzed. Furthermore, Sap2000, a widely used structural design and analysis software, were used to do numerical simulations for the test. Four finite element models with different floor assumptions, which contained detailed wood diaphragm, simplified wood diaphragm, rigid floor, flexible floor, were built and analysed under test loading conditions. At last, the calculation results were compared with the test results to calibrate the model.

2 STRUCTURAL TEST

2.1 SPECIMENS

The testing specimen considered in this study represented a simply one storey concrete frame with timber diaphragm on top. The structure’s height was 2.1 m with width 3 m and length 4 m. Three specimens with different layout of floor system, which contained full sheathed diaphragm, sheathed diaphragm with openings and no diaphragm, as shown in Figure 1, were built to be tested under monotonic lateral load. Due to the maximum force applied to the structure was small and would cause no cracks in the concrete frames, three specimens could use the same concrete frame, only the floor system would be reconstructed.

(a) Specimen 1- Full sheathed diaphragm
2.2 MATERIALS & CONSTRUCTION DETAILS

Concrete used to build up the frame was C30. The arrangement of reinforcing bars in the concrete beams and columns are shown in Figure 2. The foundation beam was connected to the ground with anchor bolts. The floor diaphragm of the test structure consisted of 38 mm x 140 mm floor joists spaced at 406 mm. The joists were connected to the rim joists with joist hangers. The connection between rim joist and concrete beams were $\phi$ 12 embedded bolts as shown in Figure 3. The floor sheathing was 12 mm OSB panel nailed to the joists with 63 mm long nails which with the 150 mm spacing along the panel edge and 300 mm spacing inside.

2.3 EXPERIMENT SET UP

The load was applied on the top of three concrete columns by three actuators. Supplied with the same oil pump, the loading forces of three actuators were always the same during the test.

Fourteen transducers, as shown in Figure 5, were used for the displacement observation during the test. Transducer 1~10 were for measuring the lateral displacement of each points on the floor plan and transducer 11~13 were used to monitor the slip of the foundation. Transducer 14 was for watching whether there was torsion displacement of the structure.

2.4 LOADING PROCESS

2.4.1 Monotonic load

Before the monotonic loading process, 3 KN force was applied to the structure to eliminate the gaps in the
connection between the actuator and structure. The maximum monotonic load was 10 KN and divided into 10 grades. Three specimens, in the terms of full sheathed, sheathed with openings, no floor, were tested under monotonic lateral load. Based on the calculation, there would be no cracks in the concrete frame during loading, so the three models used the same concrete frame, only the wood diaphragm floor was reconstructed after each model was tested.

2.4.2 Cyclic load
A full sheathed diaphragm specimen was rebuilt after monotonic load process and tested under cyclic load. At first, the loading was controlled by force, 24 KN lateral forces were applied to the structure with two cycles. After that, loading was controlled by displacement, using the mid-column top displacement $\Delta = 3.5$ mm as a basic parameter, the displacements applied to the column were $n \times \Delta$ until the loading reduced to 80% of the peak load. And each displacement step was cycled twice.

2.5 OBSERVATIONS

2.5.1 Monotonic load
In the monotonic loading step, no cracks were found in the concrete frame and there was no obvious deformation of the wood diaphragm. But during the loading of the specimen with no floor, the displacement of mid-column was obviously larger than the side-column.

2.5.2 Cyclic load
In the cyclic loading step, when the displacement reached $5 \Delta = 17.5$ mm, cracks showed up at the bottom of the columns and the ends of beams. When the displacement reached $7 \Delta = 24.5$ mm and the loading force was tension, nuts of the embedded bolts were sliding and making large noise. When the displacement reached $12 \Delta = 42$ mm, shear deformation was obvious but no damage was found in the nail connection between sheathing panels and joists. After the test, the deformation and cracks in the concrete frame were obvious, while the wood diaphragm maintained very well appearance. Figure 6 shows the photos after test.

2.6 DATA ANALYSIS

2.6.1 Monotonic load
The load-displacement curve of the top of side-column and mid-column are shown in Figure 7. From the comparisons of curve of three models, the followings could be found.

a) Due to the in-plane stiffness of the wood diaphragm, the displacement of middle column in full sheathed diaphragm specimen is much smaller than the no diaphragm specimen;

b) Openings lower down the wood diaphragm’s in-plane stiffness and the displacement of middle column in the sheathed with openings specimen is a little bit larger than in full sheathed specimen;

c) At the beginning of the load-displacement curve, the structure showed a higher lateral stiffness. That was because of the pistons in the actuators needed a start force. The back-side curve showed the real stiffness of the structure.

Figure 6: Photos after the test
2.6.2 Cyclic load

Hysteretic curve of mid-column and side-column are showed in Figure 8. From the curve of mid-column, it is observed that when the pushing force was under 55 KN, the curve appeared to be linear. While the load was over 60 KN, the structure became yielding. During the pushing force was applied, the curve kept linear until 44 KN. The hysteretic loop was unsymmetrical and the maximum pushing load was 68 KN, larger than the pulling load which was 54 KN. The curve of side-column was even more unsymmetrical. That was because of the nut-siding of embedded bolts which connected the wood diaphragm to the concrete beams, making it impossible to transfer the pulling load from mid-column to the side-column.

3 FINITE ELEMENT MODELS

There are two different assumptions for the floor’s in-plane stiffness in structural analysis under lateral load, rigid floor assumption and flexible floor assumption. For rigid floor assumption, the floor is considered as a rigid panel under the lateral load and all the points on the floor have same horizontal displacements. In this case, the lateral force would be distributed by the stiffness of the lateral resistance elements. While, for flexible floor assumption, the floor system’s in-plane stiffness is zero, all the lateral force distribution is based on how much vertical load each lateral force resist elements take. In fact, from the test, it is found that the in-plane stiffness of the light frame wood diaphragm is between the rigid floor and flexible floor. So based the different assumptions of the floor’s in-plane stiffness, four finite element model are built: Model 1-detailed wood diaphragm model, Model 2-simplified diaphragm model, Model 3-rigid floor model and Model 4-flexible floor model. Sap2000, a widely used structural design and analysis software, is used for finite element modelling.
3.1 MODEL 1-DETAILED WOOD DIAPHRAGM MODEL

Detailed wood diaphragm model simulates all the structural members. Beam element is used to simulate the concrete frame and wood joists. Shell element is used to simulate the OSB sheathings. The connections between joists are joist hangers which can be simulated as pin joints. Wood diaphragm is connected to concrete beam by embedded bolts which can be simulated as springs which both can take axial force and vertical shear force. Nonlinear springs are used for the simulation of nail connections between OSB sheathings and timber joists. The load-slip curve is obtained from nail test. Because the nails load-slip curves of two perpendicular directions are pretty close, mean value of the two curves is used for the nonlinear springs’ load-slip curve. The parameters of the numerical structural model are listed in Table 1.

Table 1: Parameters of the numerical structural element

<table>
<thead>
<tr>
<th>Structural members</th>
<th>Structural elements</th>
<th>Material parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete frame (Beams &amp; Columns)</td>
<td>Frame</td>
<td>Concrete: $E=29000$ Mpa, Steel bar: $E=203000$ Mpa</td>
</tr>
<tr>
<td>Floor joist</td>
<td>Frame</td>
<td>SPF: $E=9500$ Mpa, $E_1=5100$ Mpa, $E_2=E_3=1500$ Mpa, $G=1000$ Mpa</td>
</tr>
<tr>
<td>OSB sheathing</td>
<td>Shell</td>
<td></td>
</tr>
<tr>
<td>Nail connections between joists and sheathings</td>
<td>Link</td>
<td>$K_i=Rigid$, $K_s=K_d$ (Based on nail test curve)</td>
</tr>
<tr>
<td>Nail connections between joists</td>
<td>Pin-joint</td>
<td>Pin-joint</td>
</tr>
<tr>
<td>Embedded bolts</td>
<td>Link</td>
<td>$K_i=Rigid$, $K_s=Rigid$, $K_d=0$</td>
</tr>
</tbody>
</table>

2. Shell: $E_r$—Modulus of elasticity along thickness, $E_2, E_3$—Modulus of elasticity along wideness, $G$—Shear modulus.
3. Link: $K_i, K_s, K_d$—Stiffness of the spring along local coordinate axis 1, 2, 3. Axis 1 is the length direction; axis 2 and axis 3 are perpendicular to axis 1.

3.2 MODEL 2-SIMPLIFIED WOOD DIAPHRAGM MODEL

For a real large hybrid structure, it is very time-consuming and complex to set up detailed diaphragm models for calculation. In order to solve this problem, simplified model is raised. One way for simplification is to replace the wood diaphragm with diagonal springs with same in-plane stiffness. In passed numerical research on seismic performance of the light frame timber structures, it is a common view that the nonlinear behaviour of the structure is caused by the wood shear walls, meanwhile, the wood diaphragms are in their elastic range. So the springs in the simplified model are also linear elastic.

First step, the load-slip curve of the nail connection should be simplified to be linear springs. The method of parameters definition for wood shear walls in ASTM E2126-09 is used to define yielding strength and elastic stiffness. The simplified curve is shown in Figure 8.

Second step, replace the test nail curve with the simplified load-slip nail curve in the detailed diaphragm model, apply 1 KN lateral force in mid-span of the diaphragm and the deflection in mid-span is 0.34 mm. So the in-plane stiffness of the diaphragm is 2.94 KN/mm.

Third step, the diagonal elastic springs with the same in-plane stiffness is used to replace the wood diaphragm, as shown in Figure 9.

The stiffness of the diagonal springs should be obtained. The calculation works are shown as below.
\[ F = F_l \times \sin \alpha \]  
(1)

\[ \Delta l = \Delta \times \sin \alpha \]  
(2)

\[ F = \Delta l \times K \]  
(3)

\[ F = 0.25KN, \Delta = 0.34mm, \sin \alpha = 0.83, \]

\[ K = 1.06KN/mm \]

3.3 MODEL 3-RIGID FLOOR MODEL

In the rigid floor model, joists, sheathings and nail connections are all defined as rigid elements in order to make sure the diaphragm is a rigid panel under lateral load.

3.4 MODEL 4-FLEXIBLE FLOOR MODEL

The flexible floor model is the concrete frame which the wood diaphragm is taken away.

4 MODEL VERIFICATION

Four different finite element models are used to do the numerical simulation for loading process of the specimens 1 (full sheathed diaphragm), for both monotonic and cyclic load steps. And the numerical calculation results are compared to the results from the test for verification.

4.1 MONOTONIC LOAD

The load-displacement curves of the top of mid-column and side-column from numerical calculation and structural test are shown in Figure 11. From the figure, the followings could be observed.

a) Between the four finite element calculation curves, the detailed wood diaphragm model and the simplified diaphragm model are considerably close which means simplified model can be used to take place of the detailed model in elastic range of the structure.

b) Compared to rigid floor model and flexible floor model, the detailed diaphragm model and simplified model are more closed to the test curve.

c) In the elastic range of the structure, wood diaphragm shows a rather high in-plane stiffness which can transfer the lateral load on the mid-column to the side-column.

![Load-displacement curve of mid-column](image1)

![Load-displacement curve of side-column](image2)

Figure 11: Load-displacement curve of concrete columns from structural test and FEM calculation

4.2 CYCLIC LOAD

Cyclic load was applied by the displacement control of the top of mid-column and three force applied on the three columns were equal values. This load procedure is hard to simulate. But instead, pushover analysis can be done for the finite element models and comparisons are made between the pushover curve for the finite element models and bone curve from the test.

Figure 12 shows all the possible plastic hinges might appear in the concrete frame.

![Layout of possible plastic hinges](image3)

Figure 12: Layout of possible plastic hinges
The pushover curves of the four finite element models and the bone curves of the test are shown in Figure 13. The observing point is the top of mid-column.

From the comparison, the followings are found.

a) The ultimate bearing capacity and failure mode of the rigid floor model, detailed wood diaphragm model and simplified diaphragm model are the same with the test, which plastic hinge occurred first in the bottom of the mid-column, then in the end of the side-beams, and at last in the bottom of the side-columns.

b) The ultimate bearing capacity of the flexible floor model is relatively smaller compared to other models. That’s because when the plastic hinge in the bottom of mid-column rose up, the lateral force were not able to be transferred to the side-column, and the structure reached its ultimate stage.

c) The detailed diaphragm model curve and simplified diaphragm model curve matches well with each other. It indicates that when the hybrid structure is in plastic stage, the wood diaphragm is still in its elastic stage which makes it possible to use simplified elastic diagonal springs model to take place of the detailed diaphragm model.

![Figure 13: Bone curve of mid-column from structural test and FEM calculation](image)

5 CONCLUSIONS

This paper presented a structural test of a one-story hybrid structure with concrete frame and light frame wood diaphragm and numerical simulations for the test. Through these works, following conclusions can be reached.

a) Light frame wood diaphragm can maintain high in-plane stiffness in the elastic range and plastic range of the hybrid structure, which have a large contribution on the distribution of lateral load.

b) Light frame wood diaphragm has a high in-plane strength which guarantees the ductility and ultimate lateral bearing capacity of the whole structure.

c) The simplified wood diaphragm model can do a good simulation of the hybrid structure test, as well as the detailed diaphragm model. That makes it possible to use simplified model to take place of detailed model in analysis for the hybrid structure.

d) Compared to the flexible floor assumption, the behaviour of timber floor system under lateral load are more close to rigid floor system.

The structural model being discussed in this paper is very simple, further discussion should be carried on for full scale structures to get a better understanding of the concrete-timber hybrid structures.

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REFERENCES


