HYBRID WOOD-MASONRY WALL TEST AND VERIFICATION OF TWO-DIMENSIONAL MODELLING APPROACH

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ABSTRACT: Elevator shaft and stairwell core in multi-storey light wood frame buildings are usually constructed with non-combustible materials like reinforced concrete or masonry. As the storey limit of light wood frame buildings has been increased from 4 to 6 in the Province of British Columbia since 2009, it is beneficial to take advantage of the stiffer core to reduce building deflection under lateral loads. In this paper, two-storey hybrid wood-masonry wall systems were tested under reversed cyclic loads to simulate the seismic performance of hybrid building systems. The test data were obtained to verify a two-dimensional numerical modelling approach which would be used to predict the seismic performance of hybrid building system. The test results show that the connections failed first when the load was applied on the wood frame, while masonry core failed first when the load was applied on masonry core.

KEYWORDS: Hybrid wood-masonry wall, Wood-masonry connection, Reversed cyclic load, Numerical modelling

1 INTRODUCTION

Elevator shaft and stairwell core in multi-storey light wood frame buildings are usually constructed with non-combustible materials like reinforced concrete or masonry [1]. Although in design practice for low-rise light wood frame building up to 4-storey, the reinforced concrete or masonry core is designed separately from wood frame, the increase of storey limit from 4 to 6 may necessitate the need to rely on the stiffer core to reduce building deflection under lateral loads. Structurally attaching wood frame to a stiff core needs special attention to the seismic response of hybrid building systems as these two sub-systems have vastly different physical and mechanical properties. Research works on the performance of this type of hybrid building system is limited. In this paper, two-storey wood-masonry hybrid wall specimens, one-storey wood shear wall, two-storey reinforced masonry wall and wood-masonry connections were tested under reversed cyclic load. The purpose of these tests was to simulate the seismic performance of hybrid building system to get a good understanding on how lateral loads are transferred between wood sub-system and masonry sub-system through the connection. The results of the test program can be used as input and verification to a two-dimensional (2-d) numerical model to predict the seismic performance of multi-storey light wood frame building connected to a stiffer core.

2 EXPERIMETAL PROGRAM

Four walls were tested in this project. They were: a) one single-storey wood shear wall, b) one two-storey reinforced masonry shear wall, and c) two two-storey hybrid wood-masonry walls with load applied at the second storey of wood wall (hybrid wall HW1) and masonry wall (hybrid wall HW2). The wood-masonry connection system recommended by design engineer was also tested.

2.1 MATERIALS AND DESIGN CONFIGURATIONS

The materials and construction details of the single-storey wood shear wall and two-storey reinforced masonry shear wall are the same as those for two-storey hybrid wood-masonry shear walls. The two-storey hybrid wall consisted of a 1.4m × 2.8m reinforced masonry sub-system and a 2.4m × 2.8m wood sub-system connected together by Φ12.5mm (1/2 in.) bolts at the floor level. Fig. 1 shows the

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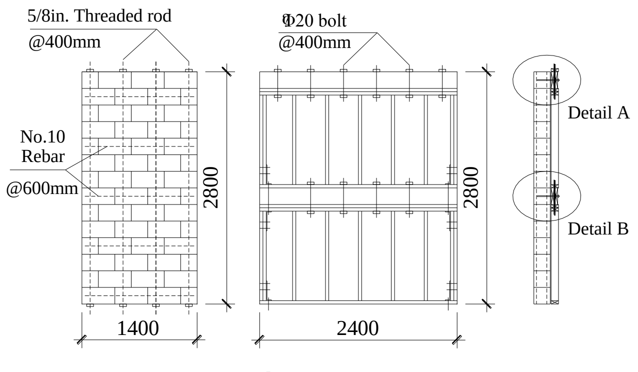
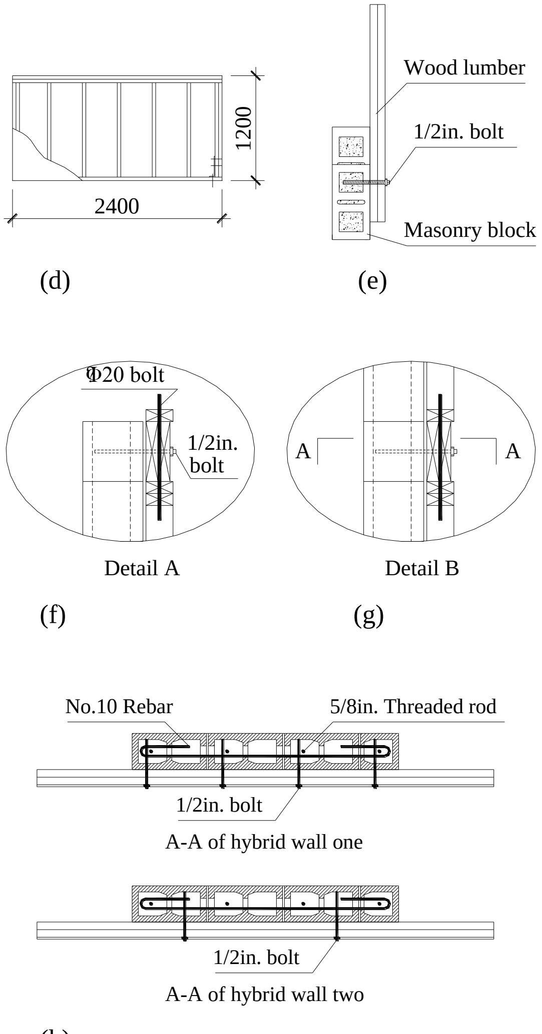
details of the wall configurations. The reinforced masonry sub-system was constructed with 20cm hollow concrete block (190 × 190 × 390mm), fully grouted, joined with Type S mortar. No. 10 rebar was located horizontally at every 600mm. Φ16mm (5/8 in.) threaded rod was used as vertical reinforcement at every 400mm (see in Fig. 1 (a)). The wood sub-system was constructed with 38mm × 89mm spruce-pine-fir (SPF) No. 2 grade and better dimension lumber spaced at 400mm and sheathed with 11mm OSB on one face. Each storey of wood sub-system had a height of 1.2m. The lumber-to-lumber nails were 83mm (3¼ in.) in length. The lumber-to-sheathing nails were 63mm (2½in.) in length. Sheathing nail spacing was 100mm at edges and 300mm in the middle. The floor headers were constructed with double 38mm × 184mm SPF No. 2 grade and better dimension lumbers. The floor headers were connected to the top plates of the 1st storey wall with toe nails at 133 mm on canter and the bottom plate of 2nd storey wall with two rows of 83 mm (3¼in.) nails at 133 mm on canter. To ensure efficient shear transfer mechanism, Φ20mm bolts were put through the floor and adjacent walls vertically at every 400mm (Fig. 1 (b)). Hold-downs (HD3B) were placed at both ends of wood walls. There were four bolt connections used on each storey of hybrid wall one (HW1), while two bolt connections in hybrid wall two (HW2) (Fig.1 (f)). For the test of wood-masonry connection system, one Φ12.5mm (1/2 in.) bolt was used to join one and a half masonry blocks and two pieces of 38mm × 184mm SPF No. 2 grade and better dimension lumbers (Fig. 1 (e)).

All of the wood materials had been kept in the environmental chamber for three weeks at a temperature of 20 ℃ and relative humidity of 65%. The wood walls were made by technician in our laboratory and the masonry walls were built by experienced mason and cured for at least 28 days before testing. Predrilled holes were left in masonry block on the floor level for placing of bolt connections.



(a) (b) (c)



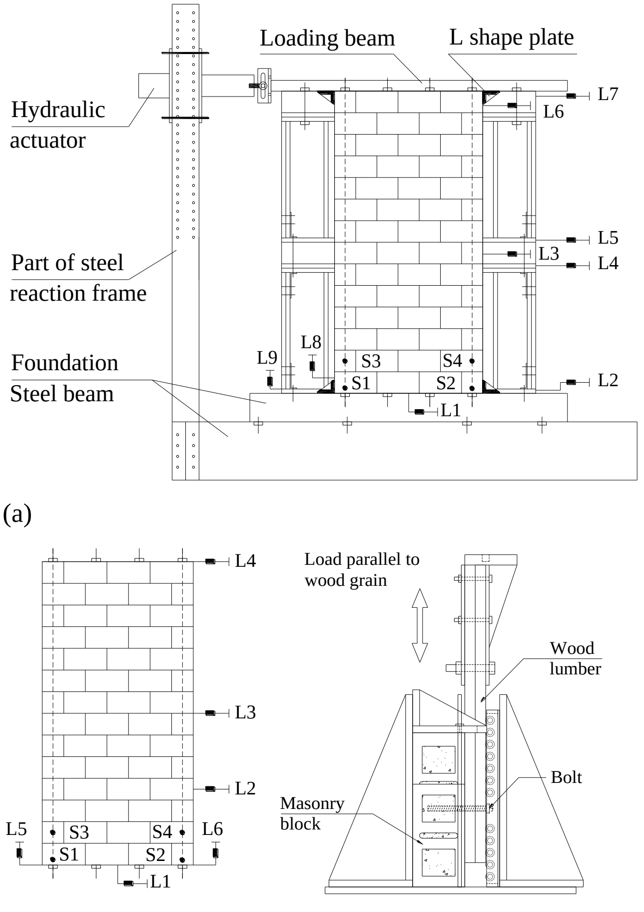
(h)

Figure 1: *Wall configurations: (a) masonry sub-system of hybrid wall; (b) wood sub-system of hybrid wall; (c) side view of hybrid wall; (d) one-storey wood wall; (e) wood-masonry connection; (f) Detail A; (g) Detail B; (h) Cross section of hybrid walls*

2.2 TEST SET UP

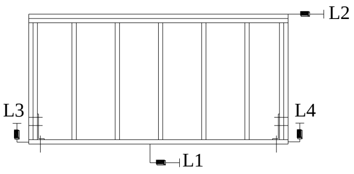
The wood sub-system of hybrid wall was bolted to a steel foundation beam with four Φ20mm bolts at 400mm and two hold-downs (HD3B) at the end of the wall. The masonry sub-system was connected with the steel foundation beam by the vertical reinfocement. L shape steel plates were placed at the ends of the masonry wall on the bottom to restrain the lateral slip (Fig. 2 (a)). In HW1, the wood sub-system was connected to the loading beam with six Φ20mm bolts at 400mm and two L shape steel plates were installed at the ends of the wood wall to block the lateral slip while the top of the masonry sub-system was free (not connected to the loading beam). In HW2, the masonry sub-system was connected to the loading beam through the threaded rod reinfrocement and two L shape steel plates at the ends of the masonry wall to restrain the lateral slip while the wood sub-system was not connected to the loading beam. The out-of-plane movement of the loading beam was restrained by guiders which had teflon material on the surface to reduce friction. The limit of hydraulic actuator in this test was 400kN and ±150mm. Reversed cyclic load was applied on the top of wood sub-system in HW1 and masonry sub-system in HW2 at a displacement controled speed of 1mm/s. Strain gauges were preplaced at the outmost reinforcement of the masonry wall at a height of 50mm and 300mm away from the bottom (S1~S4 in Fig. 2 (a)). Nine linear variable displacement transformers (LVDTs) were placed on the walls to measure the lateral and vetical dispalcements of the hybrid walls (L1~L9 in Fig. 2 (a)).

The setup of one-storey wood wall and two-storey reinforced masonry wall was the same as the hybrid walls. The loading speed of one-storey wood wall was reduced to 0.5mm/s. Four LVDTs were attached on the one-stroey wood wall (Fig. 2 (d)) and six on the two-storey masonry wall (Fig. 2 (b)). In the connection system, load was transferred between wood and masonry block in shear, (Fig. 2 (c)). Reversed cyclic load was applied on the connection parallel to wood grain at a speed of 0.5mm/s. Fig. 3 and Table 1 shows the loading protocol of these tests.



(a)

(b) (c)



(d)

Figure 2: *Test set up: (a) hybrid wall; (b) two-storey masonry wall; (c) wood-masonry connection; (d) one-storey wood wall*

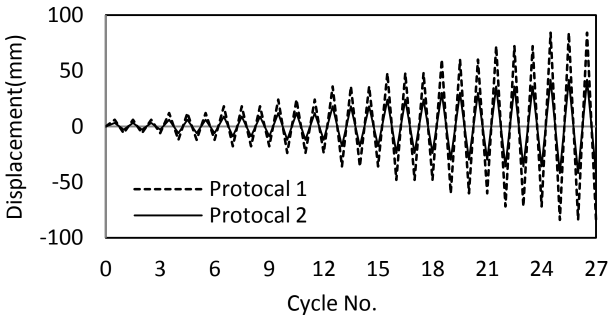


Figure 3: *Loading protocols*

Table 1: *Loading protocols*

Step	Cycles	Amplitude(mm)	
		Protocol 1	Protocol 2
1	3	6	3
2	3	12	6
3	3	18	9
4	3	24	12
5	3	36	18
6	3	48	24
7	3	60	30
8	3	72	36
9	3	84	42

Note: Protocol 1 was used for hybrid walls and two-storey masonry wall; Protocol 2 was used for wood-masonry connection and one-storey wood wall.

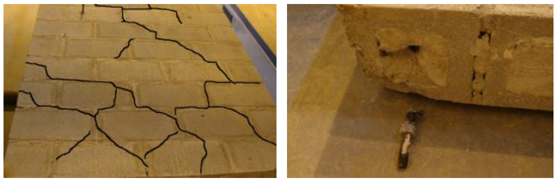
2.3 TEST RESULTS

In HW1, one of the bolts at the second-storey broke first, and then followed by failure of the other three bolts (See Fig. 4 (a)). No failure happened on the masonry wall as the ultimate resistance of masonry sub-systems was about 100kN (See Fig. 5 (c)) which was much larger than the total resistance 72kN of the four connections (18kN per bolt (See Fig. 5 (e))). In HW1, the deformation of the wood wall equals to the total deformation of masonry wall and the wood-masonry connection. As the wood shear wall has higher ultimate displacement than the total displacement of wood-masonry connection and masonry wall, no failure happened on the wood sub-system. Fig. 5 (a) shows the hysteresis loop of HW1 before the wood-masonry connections at second-storey failed. In HW2, shear cracks were developed on masonry blocks (Fig. 4

(b)) and the outmost reinforcement close to the ends of the masonry wall yielded and then broke. The deformation of the masonry wall equals to the total deformation of wood wall and the connection. As the lateral load capacity of wood shear wall is smaller than that of wood-masonry connection, this means that the force on wood-masonry connection will not be large enough to cause the connection to fail. In addition, as the wood wall can undergo larger deformation than masonry wall, this explains why failure occurred in masonry wall for HW2. Fig. 5 (b) shows the hysteresis loop of HW2. It can be seen that the hysteresis loops of HW1 and HW2 obtained in the test was not symmetric. The maximum positive resistance of HW1 was 77kN which is 18kN larger than the maximum negative resistance of HW1. The maximum positive resistance of HW2 was 153kN which is 26kN larger than the maximum negative resistance of HW2. This may be due to the damage development during the positive loading cycles.

The failure mode of two-storey masonry wall was similar to that of the masonry sub-system in HW2 (Fig. 4 (c)). One-storey wood wall failed due to the failure of sheathing nails at the edges (Fig. 4 (d)). In wood-masonry block connection test, the wood material around the bolt was compressed forming a slot hole. The bolt deformed under bending and shear stress and broke at last. Fig. 5 (c), (d) and (e) shows the hysteresis loop of two-storey masonry wall, one-storey wood wall and wood-masonry connection respectively. In these laboratory tests, the wood shear wall and wood-masonry connection show nonlinear, inelastic performance under reversed cyclic load and have stiffness degradation and pinching phenomenon to different degrees. For masonry wall, there is no clear strength degradation and the failure is brittle.

(a) Local crack of masonry block and bolt broken



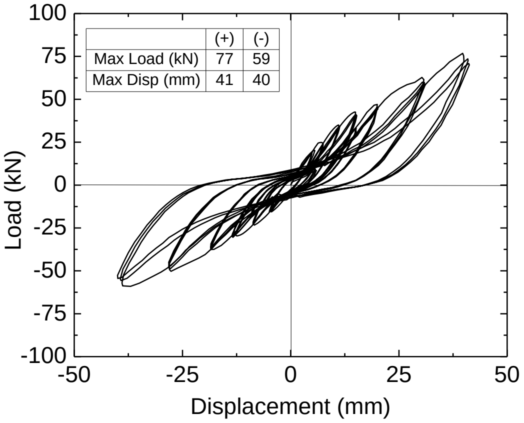
(b) Shear crack of masonry wall and threaded rod broken

(c) Shear crack of masonry block and threaded rod broken

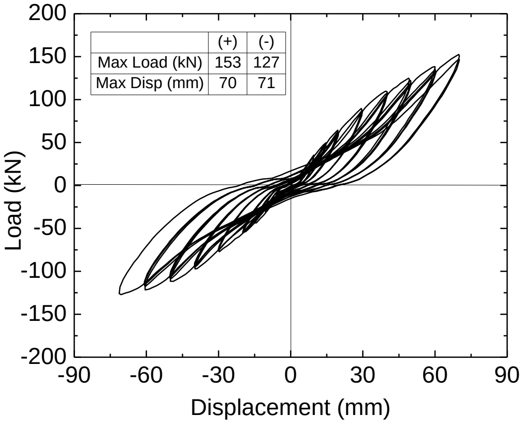
(d) Sheathing nails broken

(e) Local crack of masonry block and bolt broken

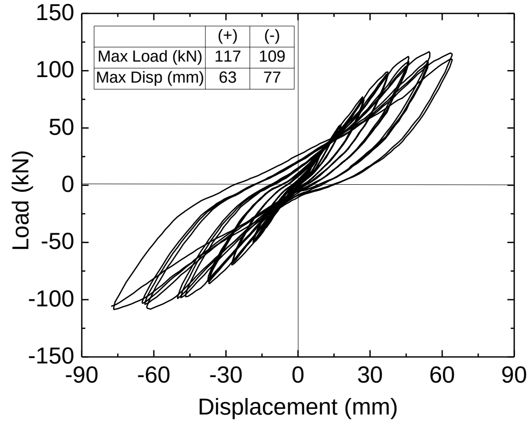
Figure 4: *Failure mode of test specimen: (a) HW1; (b) HW2; (c) two-storey masonry wall; (d) one-storey wood wall; (e) wood-masonry connection*



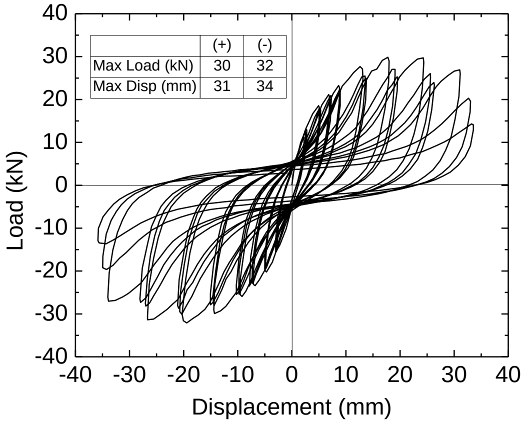
(a) Hybrid wall one



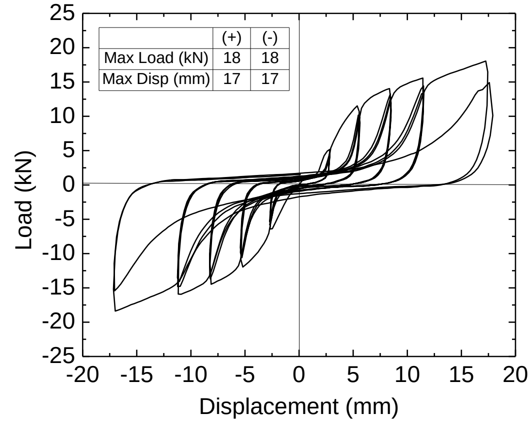
(b) Hybrid wall two



(c) 1.4m × 2.8m Masonry wall



(d) 2.4m × 1.2m wood wall



(e) Wood-masonry connection

Figure 5: *Hysteresis loop of test specimen*

3 VERIFICATION OF 2-D NUMERICAL MODEL

3.1 SYSTEM FINITE ELEMENT MODEL AND HYSTERESIS MODEL FOR ELEMENTS

A 2-d numerical model was used to analyze the seismic performance of hybrid building system consisting of light wood frame structure and reinforced masonry core. The test data obtained in this project were used to verify this 2-d model. In the 2-d model, the wood shear wall and reinforced masonry wall in a storey were considered as two super elements. The super element contains three rigid truss elements and two diagonal springs simulating the lateral hysteretic performance of the walls. The two super elements were connected by a pair of hysteretic springs that represent the bolted connections. Fig. 6 shows the schematic of 2-d modeling approach.

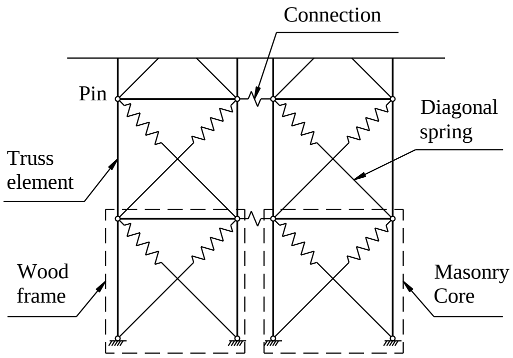
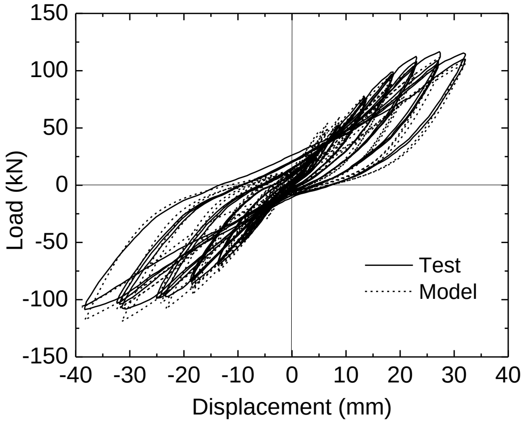


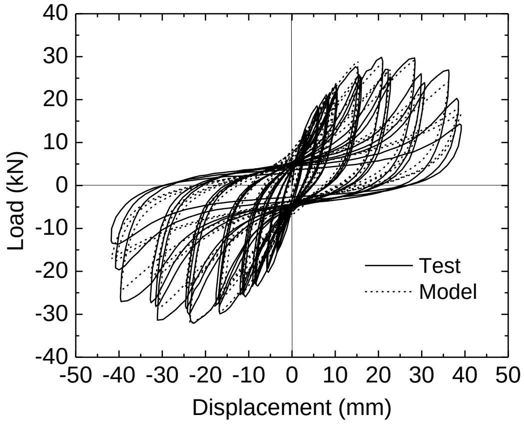
Figure 6: *Schematic of 2-d modelling approach*

This 2-d model was implemented using the commercial software ABAQUS V6.10 together with a user-developed subroutine that incorporates the Bouc-Wen-Barber-Wen (BWBN) hysteresis model [2]. The BWBN model contains 13 parameters to describe the hysteresis performance of the wall elements and connections. Detailed explanation of the significance of each parameter and equation controlling the hysteresis loops can be found in reference [3]. The lateral deformation of wood and masonry wall was assumed to be proportional to wall's height. So the hysteresis loops of wood wall (1.2m in height) and masonry wall (2.8m in height) tested in this project can be scaled to derive the loops of walls with target height of 1.4m. Fig. 7 shows the comparison of hysteresis loop of scaled test data and the numerical model. The 13 parameters of each BWBN model are calibrated with ±10% difference of dissipated energy (see Fig. 8).



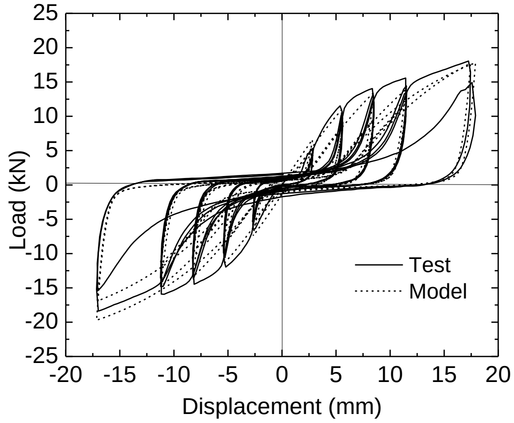
α_0=0.01
β=0.02
γ=-0.005
n=1.2
ω=2.645
δ_η=2e-5
δ_ν=2e-5
ψ=1.2
δ_ψ=0.2
q=0.02
ζ_o=0.84
p=0.09
ξ_o=1.5e-5

(a) 1.4m × 1.4m Masonry wall



α_0=0.01
β=0.21
γ=-0.11
n=1.0
ω=0.97
δ_η=1e-5
δ_ν=1e-5
ψ=3.5
δ_ψ=0.17
q=0.08
ζ_o=0.968
p=0.105
ξ_o=1.5e-5

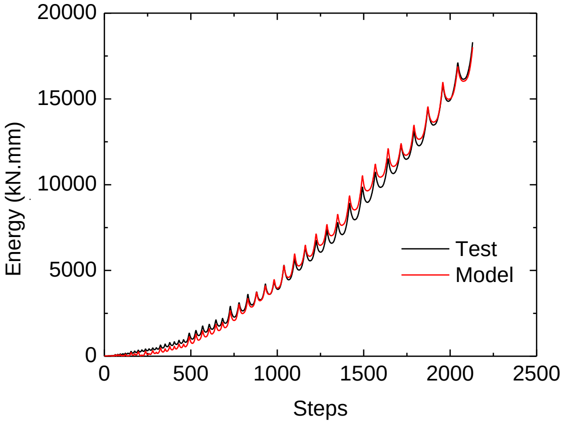
(b) 2.4m × 1.4m wood wall



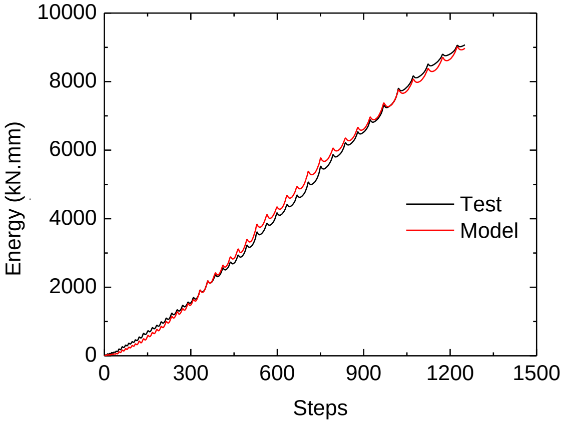
α_0=0.005
β=0.52
γ=-0.45
n=1.0
ω=1.62
δ_η=2e-4
δ_ν=5e-4
ψ=0.58
δ_ψ=0.02
q=0.015
ζ_o=0.976
p=0.48
ξ_o=1.5e-5

(c) Wood-masonry connection

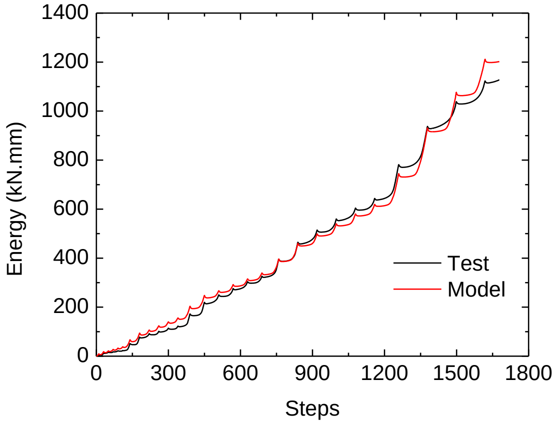
Figure 7: *Comparison of hysteresis loops of test and modelling analysis*



(a) 1.4m × 1.4m Masonry wall



(b) 2.4m × 1.4m wood wall

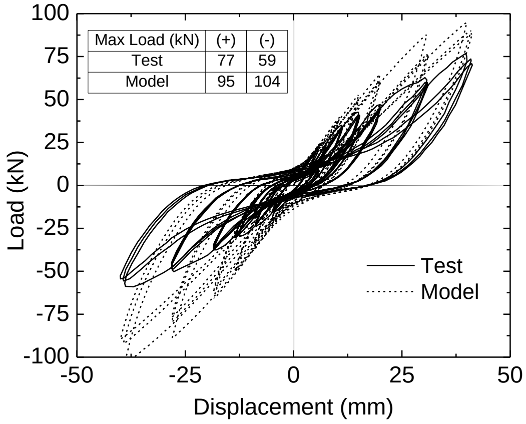


(c) Wood-masonry connection

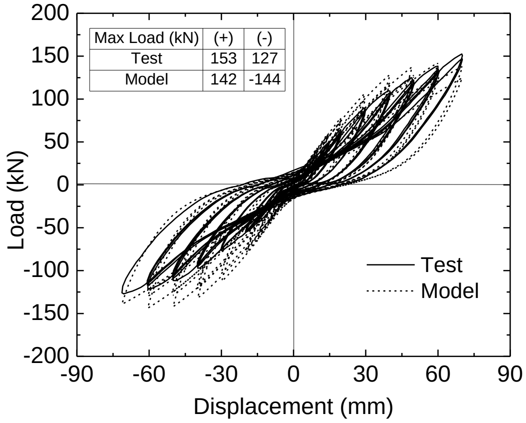
Figure 8: *Comparison of energy dissipation of test data and BWBN model*

3.2 SYSTEM MODEL VERIFICATION

The 2-storey hybrid wall models HW1 and HW2 were loaded with the same displacement history as shown in Fig. 5 (a) and (b). Fig. 8 (a) shows the comparison of hysteresis loops of test and modeling results of HW1. The maximum resistance of the HW1 in modeling analysis was 23% greater on the positive cycle and 76% greater on the negative cycle than that of test values. The large discrepancy between the model prediction and the test results may be due to the variations in wood-masonry connection performance and the differences in the modelling and the test assemblies. In the test, one of the wood-masonry connections broke earlier than the other three. In the test, the 2-storey wood shear wall consists of two 1.2 m high wood shear walls and two 0.2 m floor header. In the model, the 2-storey wood shear wall system was modelled by two 1.4 m high wood shear walls. The differences in test configuration and modelling also contribute to the discrepancy in the model prediction.



(a) HW1



(b) HW2

Figure 8: *Comparison of hysteresis loops of test and model*

Fig. 8 (b) shows the comparison of hysteresis loops of test and modeling results of HW2. The maximum resistance of HW2 by modeling analysis was 7% smaller on positive cycles and 13% larger on negative cycles than that by test. The difference is not as significant as in HW1 because the failure mode of HW2 was related to the shear crack development of the masonry block and then yielding of the reinforcement, and not the connection system. From engineering prospective, the 2-d super shear wall model shown in Fig. 6 can reasonably predict the performance of hybrid building system.

4 CONCLUSIONS

A hybrid wood-masonry wall system as well as its elements was tested under reversed cyclic load in the laboratory. The wood shear wall, reinforced masonry shear wall and connection systems all exhibited highly nonlinear, inelastic, and history dependent phenomenon. When the load was applied at the top storey of wood wall, the connections failed first. This is due to the fact that the wood shear wall has higher ultimate displacement than the total displacement of wood-masonry connection and masonry wall, and the ultimate resistance of masonry wall is much larger than the total resistance of the wood-masonry connections. When the load was applied at the top storey of masonry wall, masonry wall failed first. This is because wood wall has larger deformation than masonry wall and the ultimate resistance of wood wall is smaller than that of wood-masonry connections, meaning the force on the wood-masonry connection is not large enough to cause the connection to fail. The test provides a good indication on how the load transferred between wood and masonry sub-systems when they are structurally connected. Meanwhile, a 2-d numerical modeling approach was verified on the pseudo-static level using the test data in this project. The results showed that the developed 2-d finite element system model could reasonably predict the performance of hybrid building if reliable input properties of system elements are available. This modelling approach was adopted to analyze the seismic performance of wood-masonry hybrid building system that is reported in another paper of this conference [4].

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