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Study on the Influence of Knots on the Seismic Performance of Chinese Traditional Wooden Building Beams

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Wood Knots,
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ABSTRACT

Log is widely used in Chinese traditional wooden buildings, which has good compression, bending, tensile and seismic performance, but the existence of knots in log will have a greater adverse impact on the structure. Taking the residence of Zhou Fujiu, a salt merchant in Yangzhou as an example, the building was built in the late Qing Dynasty, covering an area of 3700 square meters. Through the field investigation of Zhou Fujiu building in Yangzhou, it is found that in addition to the common natural cracks, the wooden beams with knots in the tension zone are obviously damaged. In order to further study the influence of knots on the seismic performance of wooden beams and provide relevant theoretical basis for the protection of traditional Chinese wooden buildings, six different wooden beams were designed according to the scale of 1:5.28, and the low cycle reciprocating loading test under three-point loading was carried out. The effects of knots at different positions and depths on the seismic performance of timber beams are simulated respectively. The hysteretic curve and skeleton curve of the timber beam with knots are obtained by experiments, and the stiffness degradation and energy dissipation capacity are analyzed. The results show that with the increase of the depth of the knots, the bearing capacity of the beam shows a significant decreasing trend, the hysteretic curve becomes more stable, the energy dissipation capacity decreases, and the seismic performance decreases. When there are knots on both sides of the bending and compression area, the seismic performance of the wooden beam decreases most significantly.

1. INTRODUCTION

Wood structure architecture is a typical representative of Chinese ancient architecture, which has high artistic value and practical value. Systematic analysis and research on it will help us to take better protection measures. Wooden beam is a common component in ancient buildings. It often bears the load from the roof and is an important force transfer component. The mechanical performance of wooden beam is related to the overall seismic performance of the building. For different materials and different structural forms of wood beam performance, scholars have carried out more in-depth research. Corradi et al. (2021) carried out FRP reinforcement on the defective small wooden beams, and evaluated their bending performance under static load, which confirmed the effectiveness of the reinforcement scheme. Jeong-Moon et al. (1999) conducted an experimental study on a residential building with wooden beams in North Korea, and found that its load displacement curve has obvious nonlinear and inelastic characteristics. Yeboah and Gkantou (2021) proposed a general theoretical model to estimate the flexural capacity of nsm-frp wood beams. Nubissie et al. (2011) conducted a quantitative study on the fire resistance of wood beams. A combined analytical and numerical model for predicting the fire resistance of a wooden beam is presented. Gribanov et al. (2020) studied the strength of wooden beam structures with local modification of wood in the compressed zone.

Many ancient wooden buildings in China are still standing, but with the passage of time, the impact of wood damage on the overall seismic performance of buildings is becoming increasingly prominent. In recent years, research on damaged wood structures has made some progress. Irbe et al. (2005) studied the wood

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quality loss under different fungal corrosion conditions. Campilho et al. (2009) made an experiment on the bending behavior of wood beams of the Pinus Pinaster species repaired with adhesively-bonded carbon–epoxy patches. In addition, Karagöz and Kesik (2021) have studied that carbon fiber-reinforced polymer (CFRP) strips were used to improve the mechanical behaviors of old wood samples that were damaged over time because of various environmental effects and biological factors. At present, the research on wood structure damage mainly focuses on decay and cracking, but the research on knots is rare. There are three main types of wood beam damage in Yangzhou Zhou Fujiu building, which are cracks in square beam (Fig. 1), cracks in circular beam (Fig. 2) and damaged beam with knots (Fig. 3). It can be seen that the timber beams with knots have significant damage in the tensile zone, which will have a negative impact on the overall seismic performance of the building. Based on the above phenomena, this paper studies the influence of knots on the seismic performance of wooden beams.


Figure 1. Cracks in square beam


Figure 2. Cracks in square beam


Figure 3. Damaged beam with knots

2. METHOD

In the process of field investigation of Zhou Fujiu building timber beam in Yangzhou, it is found that when there are knots in the mid span bending area of the beam, the damage effect is the most significant. Based on this, the method of slotting in the middle of the wooden beam span is used for artificial simulation, and the simulated knots have the following characteristics: the beam section decreases when in tension; When pressed, it shows mutual extrusion and sliding. The height to width ratio of wood beam section is 3:2. Combined with the actual size of the wood beam of Zhou Fujiu building in Yangzhou, the scale of the model is 1:5.28. A total of 6 wood beams with a width of 80mm, a height of 120mm, a span of 2300mm and a clear span of 2160mm are manufactured. The wood variety is American Douglas fir.

The slot position is set in the middle of the span, and two slots with a width of 2mm are set. The Members S1-1, S1-2 and S1-3 simulate the existence of knots in the bending area of timber beams (Fig. 4); The members s2-1, s2-2 and s2-3 simulate the situation that there are knots on both sides of the bending zone and tensile zone (Fig. 5).

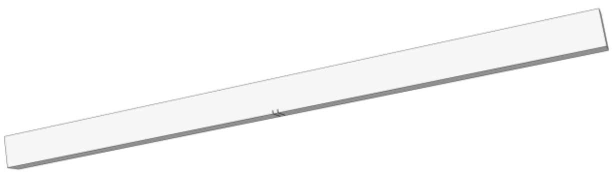


Figure 4. Three-dimensional schematic diagram of S1-1, S1-2 and

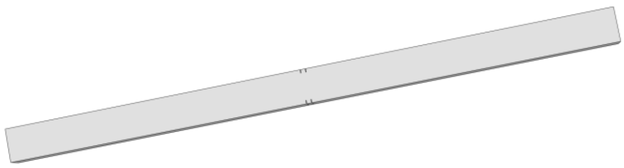


Figure 5. Three-dimensional schematic diagram of S2-1, S2-2 and S2-3

The depth of the groove is designed as 1 / 10, 1 / 5 and 1 / 3 of the beam height, 12mm, 24mm and 40mm respectively (Table 1, 2).

Table 1. Schematic diagram of S1

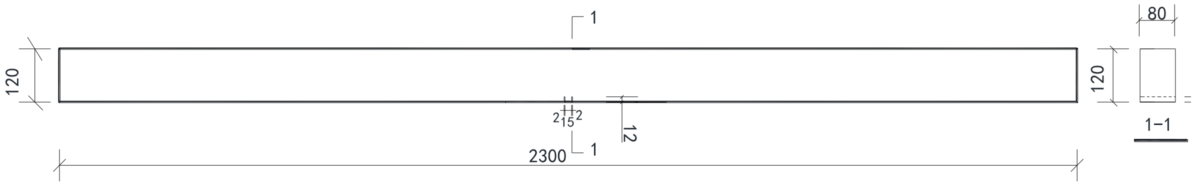
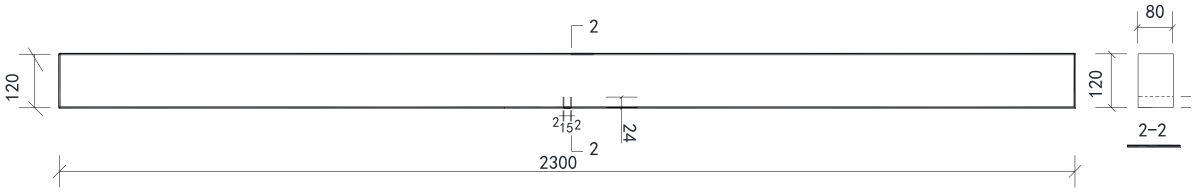
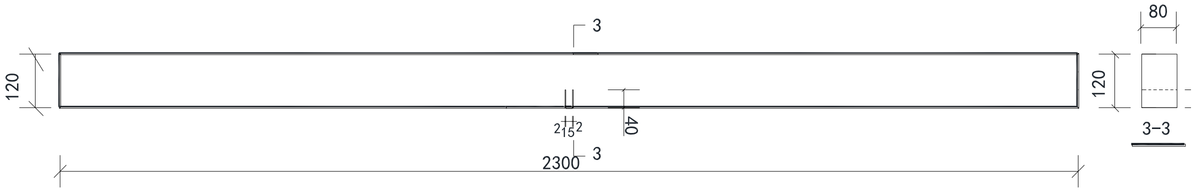
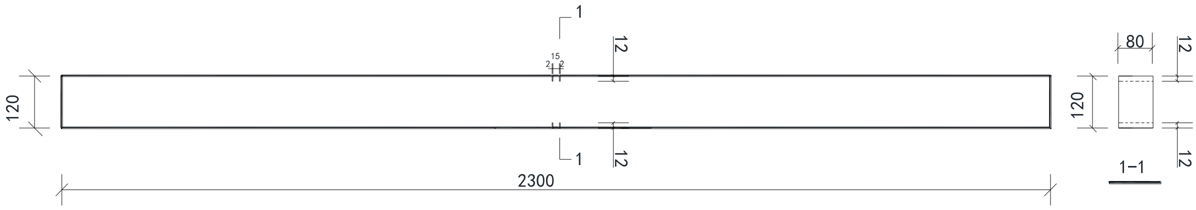
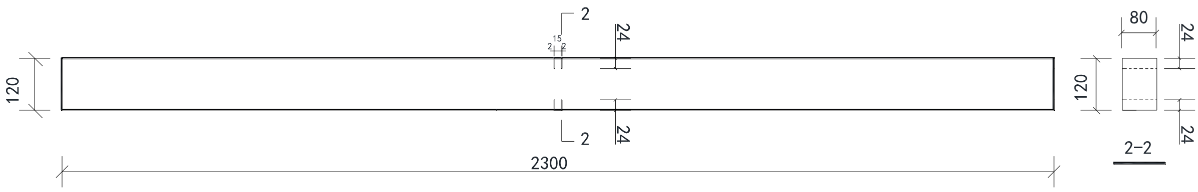
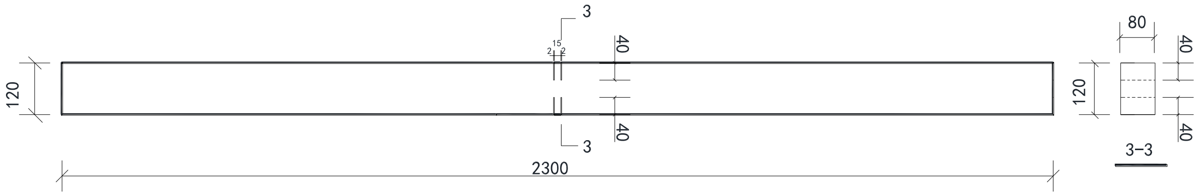
Number	Diagram
S1-1	
S1-2	
S1-3	

Table 2. Schematic diagram of S2

Number	Diagram
S2-1	
S2-2	
S2-3	

2.1. Loading Scheme

The specimen is loaded at three points, and the distance between the two loading points is 6 times of the section height, i.e. 720mm (Fig. 6).

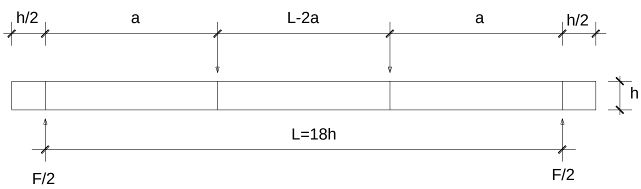


Figure 6. Schematic diagram of three point loading test of wooden beam

The low cycle reciprocating force is applied by the servo loading hydraulic press and the mode of displacement control loading is selected. The amplitude of displacement change is 10 mm during loading, and three cycles are carried out for each stage (Fig. 7).

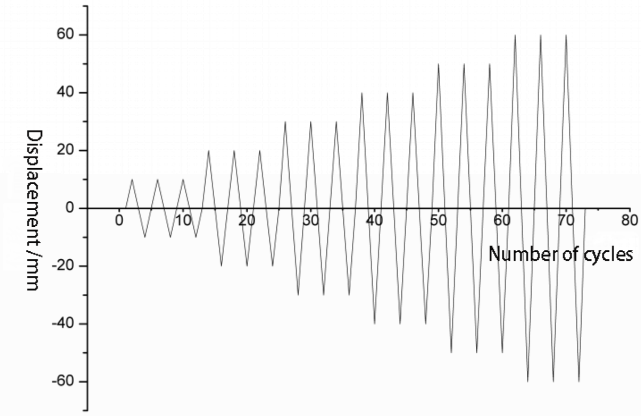


Figure 7. Loading mode of wooden beam

2.2. Experimental Phenomena

The damage of the six components finally occurred at the knots, which is consistent with the actual damage of the wooden beams of Zhou Fujiu building in Yangzhou. The experimental phenomena of the three members in group S1 are basically the same, and the cracks appear first on the side where the knots exist, and the deeper the knots are, the earlier the cracks appear. With the progress of loading, the cracks on one side of the knot gradually expand and eventually develop to the whole mid span section, resulting in the failure of the member (Fig. 8). There are knots on both sides of the middle span of the three members in group S2, and obvious cracks appear at the initial stage of loading. With the increase of displacement value, inclined cracks gradually appear along the middle of the span to both sides, and the width and length of cracks increase continuously until the members are completely destroyed (Fig. 9).

Figure 8. Midspan failure of S1 group

Figure 9. Midspan failure of S2 group

3. RESULTS

The hysteretic curves of S1 group and S2 group are obtained through the test, and the curves are processed and analyzed to study their seismic performance.

3.1. Hysteresis curve

By comparing and analyzing the hysteretic curves of six wooden beams (Fig. 10, 11, 12, 13, 14, 15), we can draw the following conclusions: 1) S1 group wooden beams only have knots on one side of the middle span, the hysteretic curves show obvious asymmetry, and the bearing capacity of the side with knots is lower than that of the intact side in each stage of loading. There are simulated knots on both sides of the middle span of S2 group timber beam, so the hysteretic curve is basically symmetrical. 2) At the later stage of loading, the stress concentration will appear at the knots, the bearing capacity of the beam will decrease rapidly, and the hysteretic curve will become an inverse S-shape. 3) When other conditions are the same, with the increase of node depth, the bearing capacity decreases more. S1-3 and S2-3 of S1 group and S2 group are the members whose bearing capacity decreases most. 4) When the depth of the knots is the same, the existence of knots on both sides is the most unfavorable to the bearing capacity of the beam.

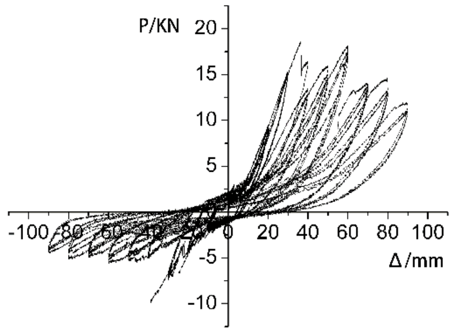


Figure 10. S1-1 hysteresis curve

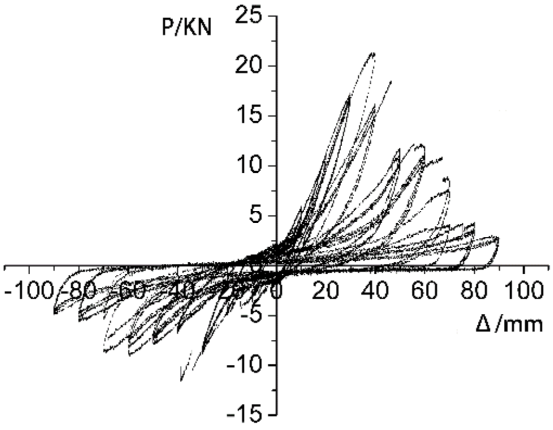


Figure 11. S1-2 hysteresis curve

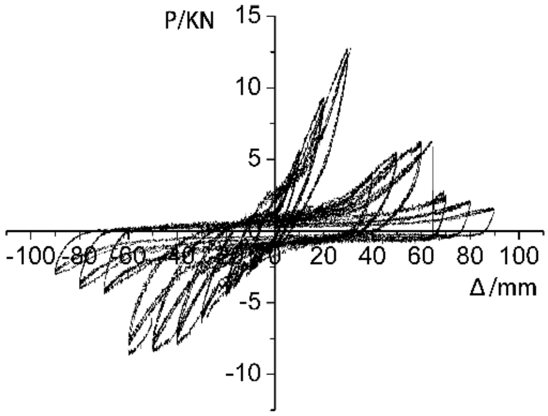


Figure 12. S1-3 hysteresis curve

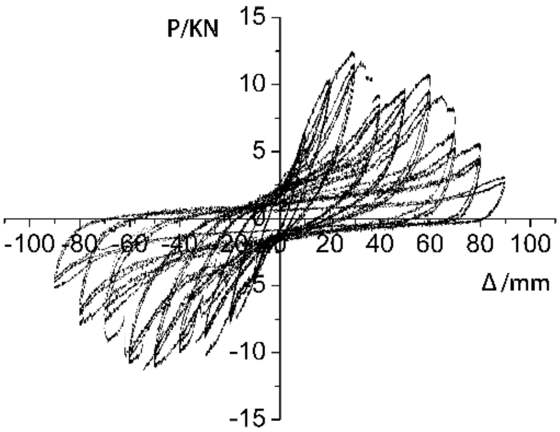


Figure 13. S2-1 hysteresis curve

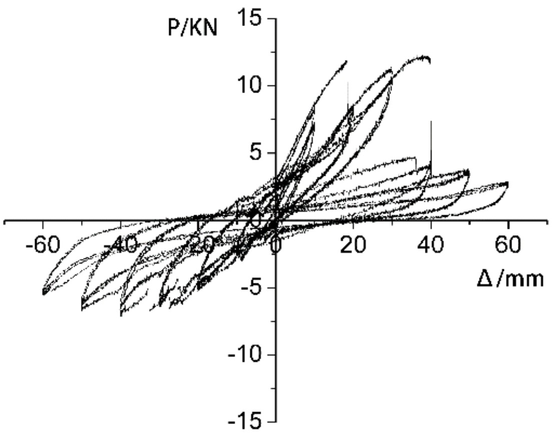


Figure 14. S2-2 hysteresis curve

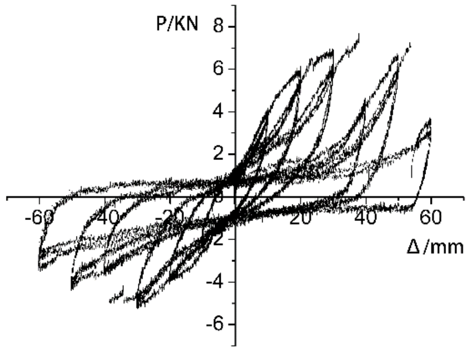


Figure 15. S2-3 hysteresis curve

3.2. Skeleton Curve

By analyzing the skeleton curves of S1 and S2 groups (Fig. 16, 17), it can be found that the deeper the knot depth is, the earlier the failure time is. Taking group S1 as an example, when the displacement is 30mm, the S1-3 member will enter the failure stage, which is obviously earlier than the other two members in the same group.

In the process of forward loading, the ultimate load of S1-1 member with 12 mm knot depth is 17.2 KN, while that of S1-3 member with 40 mm knot depth is 12.6 KN, which is 26.7% lower than that of S1-1. The decrease of ultimate load is obviously related to the increase in knot depth. Comparing the skeleton curves of the two groups of members, it can be found that when there are knots on both sides of the bending zone and tensile zone, the bearing capacity of the wooden beam decreases more significantly. Under positive loading, the depth of the knots of S2-1 is the same as that of S1-1, both are 12mm, but the ultimate load is only 12.7 KN, with a decrease of 26.1%.

Among the six members, S2-3 is the most disadvantageous in the depth and distribution of knots. There are knots with a depth of 40mm on both sides of the bending zone and tensile zone of the member, and the bearing capacity decreases most. In the forward loading process, the ultimate load of S2-3 is only 7.6 KN, which is 55.8% lower than that of S1-1 member with the least damage.

Through the above data analysis, it can be found that the influence of knots on the mechanical properties of wooden beams can not be ignored, and the depth and location of knots are important factors. If there are knots in the actual wooden beams, the possible adverse effects should be evaluated in time, and effective reinforcement or replacement measures should be taken.

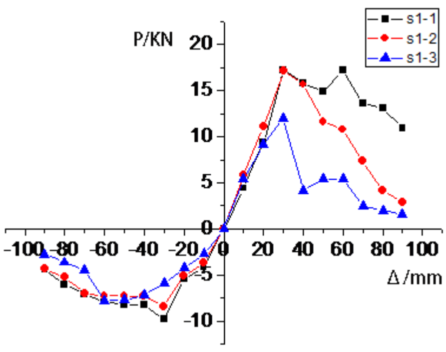


Figure 16. Skeleton curve of S1

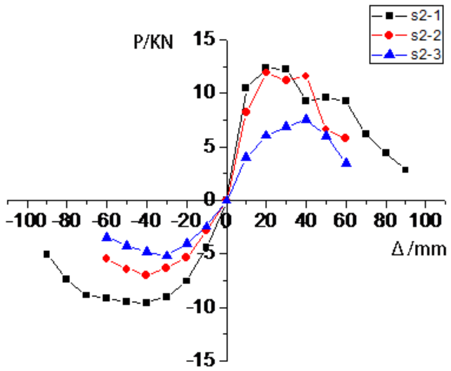


Figure 17. Skeleton curve of S2

3.3. Stiffness Degradation

It can be seen from the degradation curves that the stiffness of the six members is degraded in the process of low cycle reciprocating loading (Fig. 18, 19). The initial stiffness of the members is larger, but with the increase of loading displacement, the cracks of the members develop along the knots, leading to the gradual decline of stiffness. The degradation range of member stiffness increases with the increase of knot depth. In group S1, the stiffness degradation of S1-3 is the fastest; In S2 group, S2-3 members enter the plastic stage quickly, and the stiffness decreases significantly at the initial stage of loading.

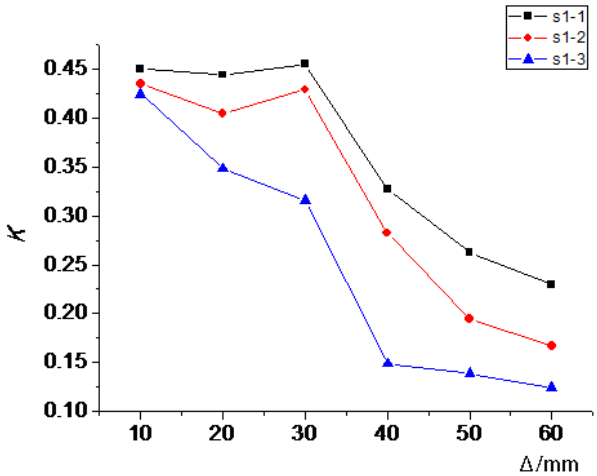


Figure 18. Stiffness degradation curve of S1

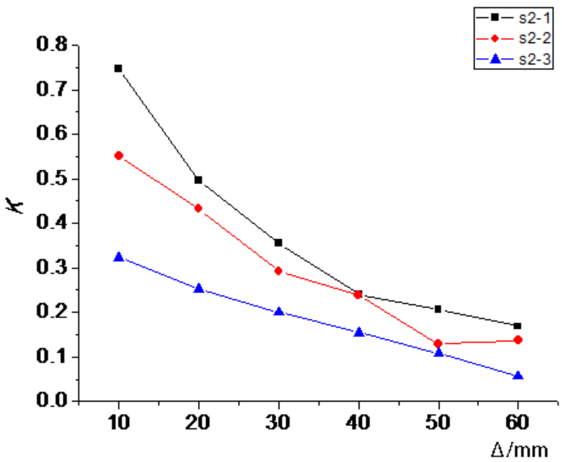


Figure 19. Stiffness degradation curve of S2

3.4. Energy Consumption Capacity

With the increase of displacement, the energy dissipation coefficient increases slightly in the initial stage and decreases rapidly in the later stage. The energy dissipation capacity of members with different depth and position of knots is different. The energy consumption coefficient of S1 group reaches temporary stability when the displacement value is 20 mm, and increases slightly (Fig. 20); When the displacement value is 40 mm, the energy dissipation coefficient decreases rapidly, and the member is damaged. It can be seen from the figure that S1-1 with the shallowest knot depth has the best energy dissipation capacity. It can be found that when there are wooden joints in the bending area and tensile area of the wooden beam, the energy consumption coefficient of the member is lower, and the decline section of the energy consumption coefficient appears earlier. When the displacement value is 30mm, the energy consumption force begins to decrease significantly (Fig. 21).

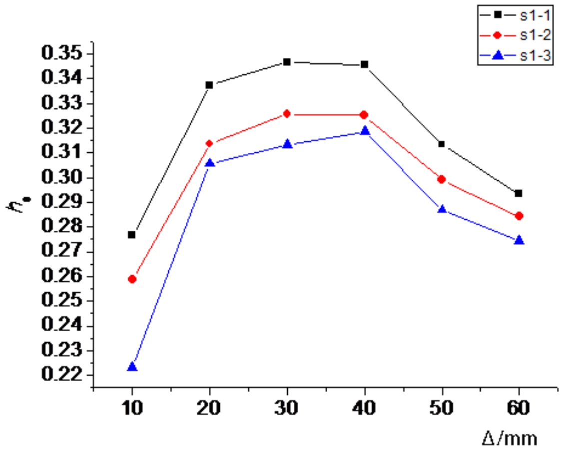


Figure 20. Energy consumption curve of S1

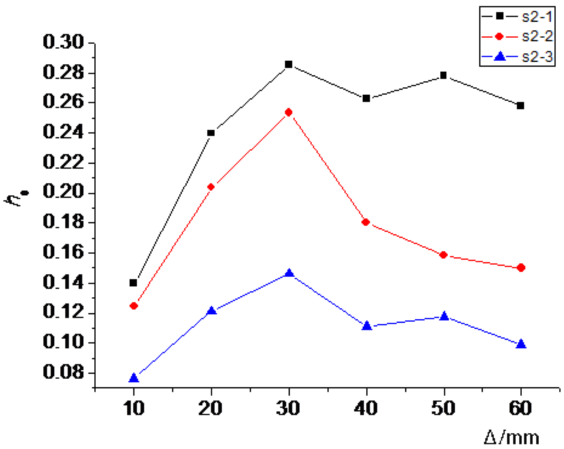


Figure 21. Energy consumption curve of S2

4. CONCLUSION

1) In the test, the failure position of the wooden beam mainly occurs in the middle of the span, and the failure cracks develop from the middle of the span to both sides of the beam. The failure mode is consistent with the actual failure mode of Zhou Fujiu building in the investigation site.

2) The deeper the depth of the knot, the weaker the bearing capacity, the more significant the stiffness degradation, the weaker the energy dissipation capacity and the worse the seismic performance. Especially when the depth of the knot reaches 1 / 3 of the beam height, the beam is not suitable for continuous bearing, which should be paid enough attention to.

3) When there are knots in the mid span bending area and tension area, the bearing capacity of the timber beam will lose rapidly, which will affect the stability of the whole building structure, which is the most unfavorable to the earthquake resistance.

4) In the maintenance of traditional Chinese wooden buildings, knots should be strictly monitored and their harmfulness should be evaluated in time. When there are deep knots in the middle of the wooden beam span, measures such as rigid wrapping should be taken for reinforcement. When there are knots in the bending area and tensile area of the wooden beam span and the depth is deep, they should be replaced in time.

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Author contributions

Shengcai Li: Investigation, Conceptualization, Methodology, Writing-Original draft
Tianhao Fan: Data curation, Writing-Original draft preparation, Software, Validation.
Donato Abruzzese: Validation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest

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