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Study on failure mechanisms and lateral strength evaluation of RC frame with CLT infill

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Infill walls Infilled RC frame

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1. Introduction

CLT is a promising eco-friendly construction material with relatively high shear strength which could be used as shear walls in new timber buildings. Another aspect that is still under study is to use CLT panels as shear wall in other structures such as steel or RC buildings. Recently, a steel frame building with CLT infill walls was constructed in Japan as shown in Figure 1. CLT infills could be used in new buildings or as retrofitting for old RC buildings to improves seismic capacity. However, limited studies are done in this direction such as experiments by Haba et al.[1]. In these experiments, Although several experiments were conducted, mainly one failure type was observed which is a shear failure in the RC columns and sliding at top of CLT infill, that will be discussed later. Many other failure mechanisms of such hybrid structures are possible which is overlooked in previous studies. Therefore, the objective of this paper is to investigate and evaluate possible failures of RC frame with post-installed CLT.

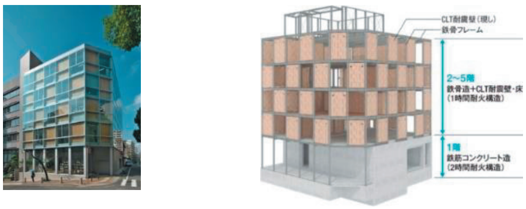


Figure 1: Actual building of steel frames with CLT infill [2].

2. Failure modes and capacity evaluation

Although CLT Infill in RC frames is a new concept, infill walls in general or post-installed walls are a common structure. A commonly used infill as seismic retrofitting elements inside a frame are masonry infill walls or RC walls or steel braces. The main difference is that material properties of CLT panel is different which may completely alter its performances which has not been investigated in past studies.

2.1 Column shear failure

This is the failure that was observed in Haba et al. [1] experiments. This failure happens when the shear capacity for the columns is less than the flexural capacity. Failure capacity can be calculated by Eq. 1

$$Q_{sh} = 2 \times Q_{su} + Q_{joint} \tag{1}$$

Where Q_{su} is the column shear strength, and Q_{joint} is the strength of the CLT to RC joint at the top of CLT panel.

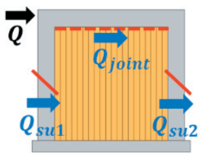


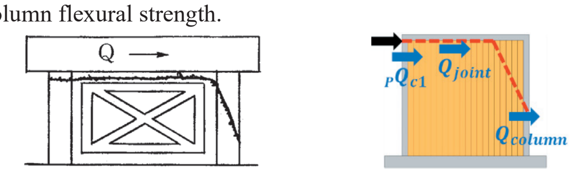
Figure 2: Column shear failure for RC frame with CLT infill.

2.2 Column punching shear failure

Having relatively strong and very stiff walls within a frame could cause a punching shear failure, which is observed in RC frames with strong steel braces as shown in Figure 3.a that is adopted from JBDPA [3]. It was also observed with ferrocement laminated masonry infills such as in the Sen et al. experiment [4]. This failure is thought to happen when CLT infill is very strong and stiff relatively to the RC frame. Failure capacity could be calculated using Eq. 2.

$$Q_{pun} = PQ_{c1} + Q_{joint} + min(Q_{su}, Q_{mu}) \tag{2}$$

Where PQ_{c1} is the punching shear capacity of the first column which is calculated as per [3], Q_{su} is column shear strength, and Q_{mu} is column flexural strength.



(a) (b)

Figure 3: (a) RC frame with steel brace punching shear [3]; (b) Punching shear failure for RC frame with CLT infill.

2.3 Frame overall flexural failure

This failure also happens when the infill is stiff relatively to the RC frame. This failure was observed in the experiment done by Lucas et al. [5] on RC frames with post-installed RC walls as well masonry infills such as Sen et al. [4]. The overall flexural capacity (Q_{fl}) could be calculated using Eq. 3 and Eq. 4 that is adopted from JBDPA [3].

$$Q_{fl} = M_u / h_0 \tag{3}$$

$$M_u = a_t f_y l_c + 0.5 N l_c \tag{4}$$

Where M_u is moment capacity, h_0 is the clear height of the column, a_t is longitudinal reinforcement area for one column, f_y is yield strength of column longitudinal reinforcement, l_c is the distance between the centers of the boundary columns and N is the total axial load applied.

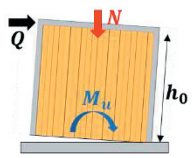


Figure 4: Overall flexural failure for RC frame with CLT infill.

2.4 CLT shear failure

This failure is thought to occur in a ductile RC frame. However, this failure is thought to occur when CLT shear capacity (S_{CLT}) have less capacity than other failure modes such as CLT compression capacity (C_{CLT}). This failure capacity can be calculated by Eq. 6 and Eq. 7.

$$Q_{CLT-s} = Q_{mu1} + Q_{mu2} + S_{CLT} \tag{6}$$

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$$S_{CLT} = \tau_{CLT} \times L_{CLT} \times t_{CLT} \quad (7)$$

Where Q_{mu1} and Q_{mu2} are first and second column capacity, S_{CLT} is CLT panel shear capacity, τ_{CLT} is CLT panel shear strength, L_{CLT} is the length of CLT panel, and t_{CLT} is the thickness.

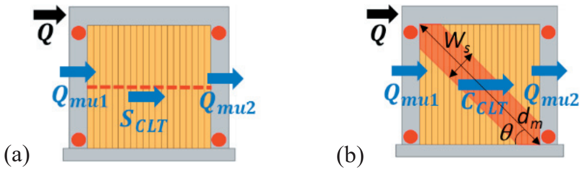

Figure 5: (a) CLT shear failure for RC frame with CLT infill; (b) CLT compression failure for RC frame with CLT infill.

2.5 CLT compression strut failure

This failure happens when the infill stiffness is lower than RC frame that has low flexural capacity (Q_{mu}). This failure was observed in the experiment done by Alwashali et al. [7] on RC frames with masonry infill. This failure capacity can be calculated by Eq. 8 and Eq. 9.

$$Q_{CLT-c} = Q_{mu1} + Q_{mu2} + C_{CLT} \quad (8)$$

$$C_{CLT} = \sigma_{CLT} \times W_{strut} \times t_{CLT} \times \cos\theta \quad (9)$$

Where C_{CLT} is CLT panel shear capacity, σ_{CLT} is CLT panel compressive strength, W_s is compression strut width with, θ is the angle between RC base and the strut with reference to Figure 5.b. The W_s, is a controversial topic which is investigate in next section

The lateral strength of CLT infilled RC frame (Q_{cal}) could be calculated by taking the minimum of the calculated lateral capacity based on the five different failure mechanism as show in Eq. 10.

$$Q_{cal} = min(Q_{sh}, Q_{pun}, Q_{fl}, Q_{CLT-c}, Q_{CLT-s}) \quad (10)$$

3. Relation of compression strut width and failure mechanism

In the case of CLT compression strut failure, strut width is mainly the value that depends on materials characteristics, and it is still poorly understood. A simple approach is to assume method used for masonry infill is applicable for CLT infill, such as FEMA-306 Guideline [7] and equation proposed by Sen et al. [5]. The calculations of strut width showed large variations as shown in Figure 7.a. This could lead to uncertainty in the failure mechanism. The variation of lateral force for the same frame (frame used in section 4) is shown in Figure 7.b.

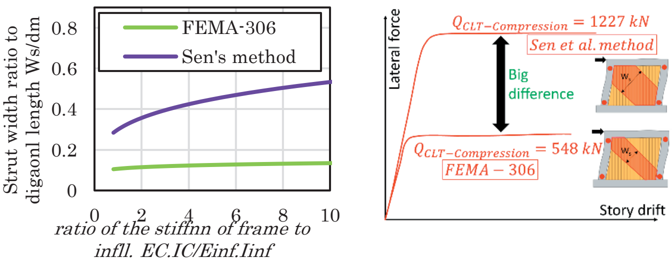

Figure 7: (left) Strut width to diagonal length vs. relative stiffness; (right) comparison of strength capacity of the two analytical methods to calculate strut width.

4. Investigation of proposed failure mechanism on a case study

In order to understand the failure mechanism well, a case study of RC frame used that was tested study [7] for masonry infill and will be used here assuming CLT infill as shown in Figure 8. The thickness of the CLT panel is assumed to be 60 mm, and shear and compression strength for CLT are 4.1 MPa and 17.35 MPa, respectively.

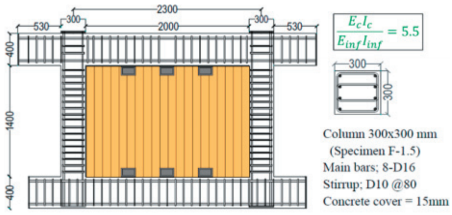

Figure 8: Case study RC frame for capacity evaluation.

Three shear connections were assumed at the top and bottom CLT infill of each have a shear strength of 80 kN. For CLT compression strut failure the two methods were used FEMA 306 and Sen et al. (which are actually for masonry infill, not CLT as discussed earlier). The expected strength capacity and expected failure mechanism of each mode are shown in Figure 9. As shown in Figure 9 compression failure mode is expected if FEMA [7] strut width is used. However, in the case of the Sen et al. method [5], the strength of compression failure increased, and thus punching shear failure is expected. This influence of strut width can alter the expected mechanism.

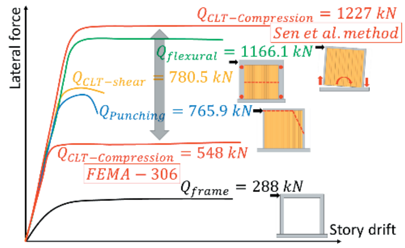

Figure 6: The capacity of RC frame for each probable failure.

5. Conclusion

In this paper, Several probable failure mechanisms for RC frames with CLT infill was investigated.

- The behavior of CLT infilled RC frame could be predicted using the proposed evaluation methods except for compression failure.
- For the compression failure evaluation method, the approach of calculating strut width greatly affects the results, and thus changing the failure mechanism of the RC frame. The predicted failure mechanism changes from ductile compression failure to brittle punching shear failure based on the calculating method of the strut width, and thus further experimental investigation is still needed.

References

[1] Haba, R., et al. "Development of CLT panels bond-in method for seismic retrofitting of RC frame structure." J. Struct. Constr. Eng 81 (2016): 1299-1308.

[2] 日経 Xtech 2019, accessed 2 April 2021, <https://xtech.nikkei.com>.

[3] Japan Building Digester Prevention Association (JBDPA) standard, 2001.

[4] Sen et al. (2020a), Experimental investigation and capacity evaluation of ferro-cement laminated masonry infilled RC frame,17th WCEE.

[5] Lucas et al. (2020), A potential vulnerability in high-strength reinforced concrete shear wall retrofits, 17th WCEE.

[6] Alwashali et al., Experimental investigation of influences of several parameters on seismic capacity of masonry infilled reinforced concrete frame, Engineering Structures 189 (2019): 11-24.

[7] FEDERAL EMERGENCY MANAGEMENT AGENCY. FEMA 274: NEHRP commentary on the guidelines for the seismic rehabilitation of buildings, BSSC Seismic Rehabilitation Project, Washington, DC, 1997.

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