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Study on the Seismic Performance Evaluation of RC Frame with CLT Panels
Part 3 Analytical modelling and application to the seismic performance evaluation

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MS model Reinforced concrete
Rocking mechanism Structural test
Wooden walls

1. Introduction

The seismic performance of the RC frame with CLT infills was experimentally investigated, as explained in **Part 1** and **Part 2**. This part explains a proposed analytical model to simulate the RC frame with CLT infills based on the experimental results in **Part 2**. Moreover, the reliability/applicability of the proposed analytical model is verified by comparing the experimental and analytical results.

2. Analytical Study

2.1 Modelling of the specimen

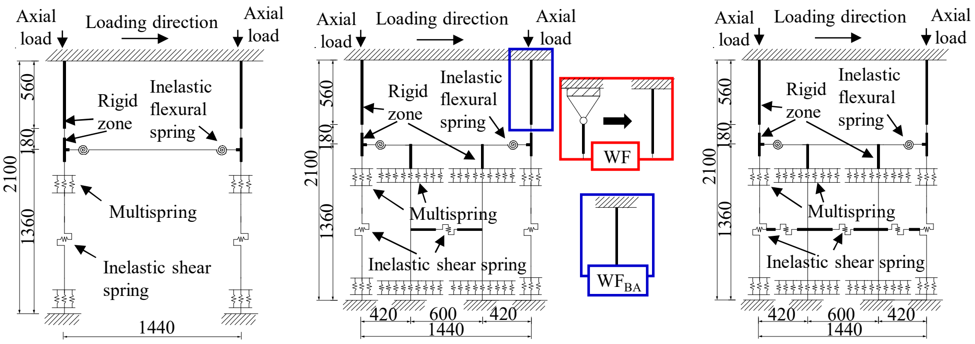
Based on the experimental results in **Part 2**, each specimen was modelled, as shown in **Fig. 1**. Pushover analysis was performed for each specimen applying the incremental loads at the top of the specimen similar to the experimental loading conditions. The modelling of the frame structure is described in Ref. [3] for more information. The material properties used for the analytical study are summarized in **Tables 2** and **3** of **Part 1**.

2.2 Specimen BF

For the flexural behavior of the column, the MS model was used at the both ends, as shown in **Fig. 1(a)**, to simulate the M-N interaction, and the column section was divided into 10 equal segments with depth of 20 mm and width of 220 mm. The plastic hinge length L_p was assumed as 1.25 times (= 300 mm) the column depth (D) based on the experimental result as illustrated in **Part 2** (**Fig. 3** in **Part 2**). For the material models for the MS model, the Hognestad model[4] was used for the concrete, whereas the bilinear model with post-yield stiffness of 0.1% of initial stiffness was used for the reinforcement. Since shear cracks were observed in the columns during the experiment, the shear properties of the columns were represented by the nonlinear shear spring, as shown in **Fig. 2**. The shear crack strength (Q_{cr}) and ultimate shear strength (Q_{su}) of the shear spring model were evaluated based on the Japanese guidelines[5], while the ultimate shear deformation angle (R_u) was assumed to be 0.4% rad[6]. The beams were replaced by a line element, and its restoring force characteristics for bending was represented by a trilinear model, while an elastic spring was used to represent the shear behavior. Other details of the material modelling are described in the authors' previous study[3].

2.3 Specimens WF, WF$_{BA}$ and WF$_{BCA}$

The RC frame was modelled in the same manner as those for the specimen BF. The MS model was used at both ends of each CLT panel to represents its flexural behavior, and its section was divided into 10 equal parts with depth of 60 mm and thickness of 86 mm. **Figure 3** shows the material model for the CLT infills used for the MS model. Based on the compression test results of the material, the CLT infills adopted the curvilinear stiffness reduction type on the compression side. Since the CLT infills showed the rocking behavior as explained in **Part 2**, its tensile strength was neglected for the material modelling. The shear properties of CLT infills were represented by elastic. The CLT infills plastic hinge length ($_cL_p$) was assumed to be 2.5 times the infills thickness (=215 mm). Due to the lack of clear evidence about the CLT infills plastic hinge length, it was assumed similar to that of RC shear wall[7]. Hence, the appropriateness of the assumed plastic hinge length ($_cL_p$) should be verified in future. For the modelling, the line element representing the CLT infills were assumed to have rigid zone with length equal to half of the beam depth at the top, as shown in **Fig. 1(b)** and **(c)**. As shown in **Fig. 4**, the shear properties of the anchor between the CLT infills



(a) Specimen BF (b) Specimen WF, WF$_{BA}$ (c) Specimen WF$_{BCA}$

Fig. 1 Overall analysis models for the specimens (Unit = mm)

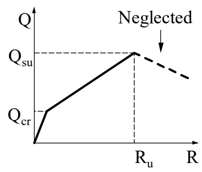


Fig. 2 Inelastic shear spring model

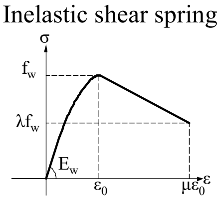


Fig. 3 CLT models for MS model

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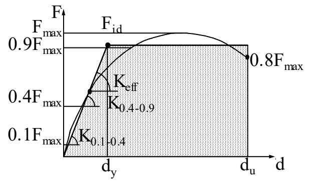


Fig. 4 Idealization of force-displacement bi-linear curve[8]

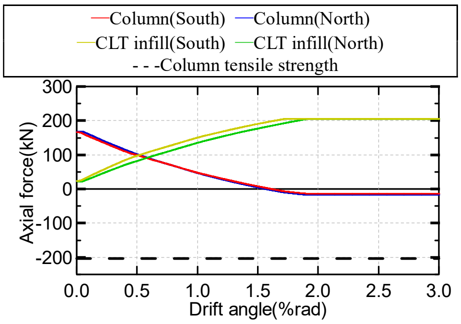
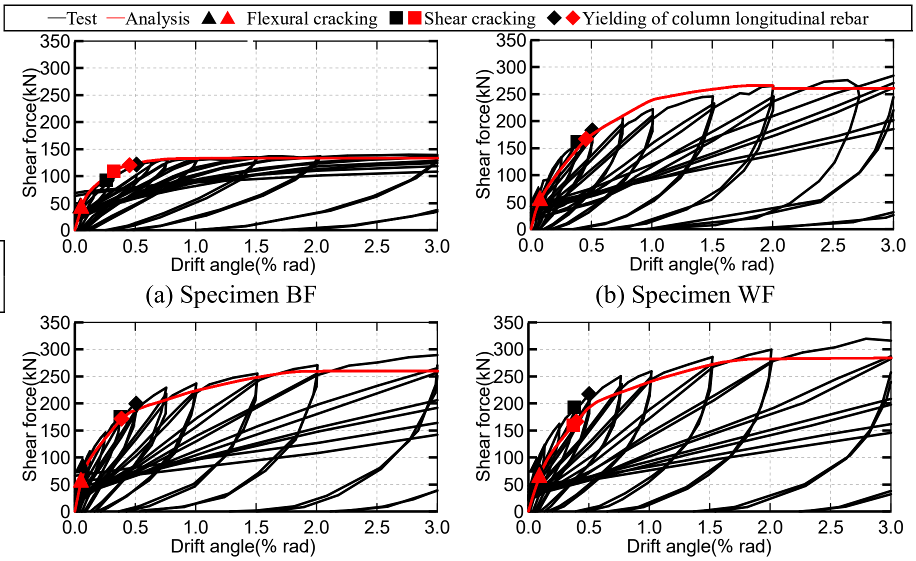


Fig. 6 Axial force of each member of RC frame with CLT infill wall (WF)



(a) Specimen BF (b) Specimen WF

(c) Specimen WF_{BA} (d) Specimen WF_{BCA}

Fig. 5 Comparison of analytical performance curves with the experimental results

were represented by a bilinear model which was modelled based on the method suggested in the past study[8] and by using additional shear test results of the CLT elements connected with two anchors. In addition, the top end condition of the second-floor column of specimen WF was changed from pin support to fixed support during the experiment, as explained in **Part 1** (**Fig. 3(a)** and **(b)** in **Part 1**). Hence, the analytical study was performed for both end conditions, i.e. for pin and fixed for the specimen WF.
The analytical model of the specimen WF_{BA} is the same as that of specimen WF since the pullout of the anchors between the CLT infills and the RC beam was visually observed before the specimen exhibited the maximum strength, as explained in **Part 2**. However, for specimen WF_{BA} the top end condition was considered as fixed support throughout the analysis, similar to the experiment.
For specimen WF_{BCA}, the modelling of the column-beam framing, CLT infills, and anchors between CLT infills are the same as those for the specimens WF and WF_{BA}. The modelling of the anchors between CLT infills and column was performed in the same way as the anchors between the CLT infills, as mentioned above.

3. Analytical Results

Figure 5 compares the analytical performance curves with the experimental results. Comparing the analytical and experimental results, it was clear that the analytical result for specimen BF had a good agreement, mainly in terms of the initial stiffness and the maximum strength after yielding of column longitudinal rebar. Similarly, the analytical performance curve and the damage progress for specimens WF and WF_{BA} showed similar behavior with the experiment, mainly up to the R = 2.0% rad. On the other hand, the analytical stiffness and the strength of specimen WF_{BCA} were a little lower than the experimental results. This might result from the fact that the analytical model did not simulate the frictional resistance at the member boundaries, and that the mechanical properties of the CLT might vary due to the different boundary conditions from those of the material tests. The analytical results also showed the column yielding mechanism of RC frame for all the specimens. **Figure 6** shows the relation between the axial force and the drift from the analysis for specimen WF (the relations were similar for other specimens with CLT infills). It was analytically confirmed that the CLT infills carried higher axial forces as the deformation increased up to a 2.0% drift, which might be the main reason why the later strength did not drop by 80% of the maximum strength even after the buckling of the column longitudinal rebar for the specimens with CLT infills, as explained in **Part 2**.
Hence, it was clarified that the proposed analytical model could be used to evaluate the seismic performance of RC frame with CLT infills with minor errors.

4. Conclusions

In this study, the analytical model was proposed to simulate the performance of RC frame with CLT infills. The comparison between the analytical and experimental results revealed that the proposed analytical model could be used for the seismic performance evaluation of the RC frame with CLT infills with limited errors. References are listed in **Part 2**.

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