NUMERICAL STUDY OF THE BEHAVIOR OF SHEAR WALLS SUBJECTED TO EARTHQUAKE LOADS

Gati Annisa Hayu1, Michael Brun2, dan Endah Wahyuni3

1 Institut Teknologi Sepuluh Nopember, email: annisagati@gmail.com
2 INSA de Lyon, email: Michael.brun@insa-lyon.fr
3 Institut Teknologi Sepuluh Nopember, email: endah@ce.its.ac.id

ABSTRACT

Shear walls are the reinforced concrete elements that provide substantial strength and stiffness as well as the deformation capacity needed to meet the demands of strong earthquake ground motion. The main function of shear walls is to resist the lateral loads like earthquake loads and wind loads.

Pseudo-dynamic test of low-rise shear walls have been carried out by Électricité de France and COGEMA at ELSA laboratory of the Joint Research Centre in 1997-1998. The purpose of writing this thesis is to perform numerical modeling of the behavior of shear walls when subjected to seismic loads. 2D modeling is done using software named CAST3M.

Two types of shear walls are investigated: shear walls T8 characterized by longitudinal and transversal reinforce ratio of 0.4% and shear walls T13 that has the same reinforce ratio with T8 but retrofitted by CFRP material.

Two types of loading in this numerical study are the pushover and the dynamic loading. Dynamic loading is done with 3 variations of acceleration: a(t), 1.4 x a(t), and 1.8 x a(t) for T8 and a(t), 1.8 x a(t), and 2.6 x a(t) for T13.

These modeling results are the deformation curve of concrete, the deformation curve of reinforcement, the displacement-time curve, the force-time curve, the displacement-force curve, and the hysteresis curve. From the force-time curve and the displacement time curve, it can be seen that the results of numerical modeling approach the experimental results. The results of shear walls T13 are closer to the experimental results than shear walls T8. This is influenced by the size of the mesh.

Keywords: CAST3M, dynamics, pushover, shear walls, T8, T13

1. INTRODUCTION

According to the report of the Chi-Chi earthquake in 1999, shear walls play an important role as part of the earthquake resistant element in low-rise reinforced concrete (RC) building [1]. The RC shear walls can effectively resist horizontal forces and reduce the risk due to an earthquake. In nuclear power plants, massive short shear walls and squat shear walls are used. For these short shear walls, bending and sliding shear failure don’t occur. Many experiments have been conducted by researchers on the short shear walls [2].

2. STUDY REFERENCES

A. CAST3M Program

Cast3m is a computer code for structural analysis by finite element method and the modeling in fluids mechanics. This code was developed by Service d’Etudes Mécaniques et Thermiques (SEMT) of Département de Modélisation des Systèmes et Structures (DM2S) of Commissariat français à l’Energie Atomique (CEA). It presents a complete system, incorporating not only the calculation function, but
also the functions of model construction (pre-processor) and treatment results (post-processor). Sometimes it is defined as “Matlab finite element”.

B. The Material Models Used

- **Concrete Integrates**
  The concrete is developed within the framework of the standard elastoplastic in plane stress condition. Typical surface in this model are the fracture surface and the load surface. There are 2 fracture surfaces, the compression area and the traction area.

- **Crack Concrete**
  The elastoplastic behavior of the concrete transforms into orthotropic behavior on the mark of the crack [3]. The first law uniaxial is relative to the first direction which coincides with the direction of the major principal stress when the stress reaches the failure surface. While on the second law uniaxial, the second direction of the crack is determined perpendicular from the first direction of the crack.

- **Steel Model**
  The behavior model of the steel is an elastoplastic model to positive hardening defined by the elastic characteristics and hardening slope after the plastification.

- **CFRP**
  The CFRP strips are represented by uniaxial bars and modeled by three bar elements whose total section is equal to the section of the 75 mm wide CFRP plate.

- **Steel-Concrete bond**
  The cyclic behavior model of the connection between steel and concrete is implemented in the CAST3M. This model is based on the mechanism of resistance and the degradation of the bond occurring during uplift of rebar embedded in a block of concrete [4].

C. The Presentation of The Structure

The structure is idealized as a system with one degree of freedom. The values of the mass M and damping are specified.

\[ K = \frac{G S_a}{h} \]

\[ f_0 = \frac{1}{2\pi} \sqrt{\frac{K}{M}} \]

\[ \rho_h = \frac{t_d}{f_e} \text{ and } \rho_v = \frac{t_d - \sigma_n}{f_e} \]

With G is the conventional shear modulus, S_a is the core section, h is the height of the wall, \( \sigma_n \) is the average vertical stress resulting from the own weight and loading device, and \( t_d \) is the average shear design.
D. Loadings

- The Quasi-static Loading
  The quasi-static load is the load that is applied slowly to the structure, it also deforms very slowly and therefore the force inertia is very low and can be neglected. There are two types of this load: the force imposed and the displacement imposed.

- The Pseudo-dynamic Loading (PSD)
  The PSD test uses on-line computer calculation and control together with experimental measurement of force to provide a realistic simulation of the dynamic behavior of shear walls [5]. The damping properties and the inertia are simulated and the properties of the stiffness are acquired from the structure [6]. The formulation of the equation of motion is:

\[
m\ddot{u}(t) + c\dot{u}(t) + r(t) = -ma(t) \tag{4}
\]

With \(m\) is the numerical mass of the shear walls, \(c\) is the numerical parameter of viscous damping, \(r(t)\) is the restoring force measuring experimentally, and \(a(t)\) is the acceleration imposed on the base of the web.

The nominal accelerogram can be obtained by multiplying the reference accelerogram with a coefficient \(k\).

\[
k = \frac{H_d}{M \Gamma_d(f_0, \xi = 0.07)} \tag{5}
\]

\[
H_d = \tau_d L e \tag{6}
\]

With \(H_d\) is the horizontal force, \(\tau_d\) is the shear, \(L\) is the length of the web, \(e\) is the thickness of the web, \(M\) is the effective mass supported by the shear walls, and \(\Gamma_d(f_0, \xi = 0.07)\) is the value of the standard spectrum DSN79 5%.

3. INVESTIGATION OF THE TEST

A. SAFE Program

The experimental is implemented using the SAFE program (Structures Armées Faiblement Elancées). It was conducted in ELSA laboratory in 1997-1998. There were 13 RC shear walls in this experimental campaign, conducted with the pseudo-dynamic method.

B. Type The Shear Walls Test

The shear walls has a height of 120 cm, a width of 300 cm, and a thickness of 20 cm.
Fig. 1 Geometry of The RC Shear Walls

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>T8</th>
<th>T13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness ($e$)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Vertical reinforcement ratio ($\rho_v$)</td>
<td>0.4 %</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Horizontal reinforcement ratio ($\rho_h$)</td>
<td>0.4 %</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Masse (M)</td>
<td>1252 x $10^3$ Kg</td>
<td>1252 x $10^3$ Kg</td>
</tr>
<tr>
<td>Design stiffness ($K_{dim}$)</td>
<td>7120 MN/m</td>
<td>7120 MN/m</td>
</tr>
<tr>
<td>Normal stress ($\sigma_n$)</td>
<td>3.4 Kg/cm²</td>
<td>3.4 Kg/cm²</td>
</tr>
<tr>
<td>Design shear stress ($\tau_{dim}$)</td>
<td>120 Kg/cm²</td>
<td>120 Kg/cm²</td>
</tr>
<tr>
<td>Design frequency ($f_d$)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Measured initial frequency ($f_0$)</td>
<td>9.6</td>
<td>10.1</td>
</tr>
<tr>
<td>Scaled factor for the design acclerogram ($k$)</td>
<td>0.329</td>
<td>0.329</td>
</tr>
<tr>
<td>Amplification factors in PSD ($a$)</td>
<td>1, 1.4, 1.8</td>
<td>1, 1.8, 2.6</td>
</tr>
</tbody>
</table>

C. Description of Testing and Testing Instruments

The horizontal load is applied on both sides of the peak of the shear walls. To submit the structure to the nearest possible loading of a pure shear, the rotation of the upper sill is blocked by a system of jacks. Device fixes the base to prevent slipping and take off.
4. NUMERICAL MODELING

Unlike the SAFE program, modeling using CAST3M is only on the web without the upper and lower sills.

<table>
<thead>
<tr>
<th>TABEL II. Characteristics of Concrete</th>
</tr>
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<tbody>
<tr>
<td>T8</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Young’s modulus</td>
</tr>
<tr>
<td>Poisson ratio</td>
</tr>
<tr>
<td>Ultimate stress in simple compression</td>
</tr>
<tr>
<td>Breaking strain in tension</td>
</tr>
<tr>
<td>Fracture strain in compression</td>
</tr>
<tr>
<td>Transfer shear factor</td>
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</tbody>
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<tr>
<th>TABEL III. Characteristics of Steel</th>
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<tbody>
<tr>
<td>Characteristics</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Young’s modulus</td>
</tr>
<tr>
<td>Poisson ratio</td>
</tr>
<tr>
<td>Strain plasticity</td>
</tr>
<tr>
<td>Ultimate strain</td>
</tr>
<tr>
<td>Ultimate stress</td>
</tr>
<tr>
<td>RHO</td>
</tr>
</tbody>
</table>
TABEL IV. Characteristics of CFRP

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>T8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>1500000 Kg/cm²</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.0</td>
</tr>
<tr>
<td>Ultimate strain</td>
<td>0.0056</td>
</tr>
<tr>
<td>Effective strain</td>
<td>0.004</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.043 cm</td>
</tr>
<tr>
<td>Width</td>
<td>7.5 cm</td>
</tr>
</tbody>
</table>

The mesh of concrete is modeled with a model quadrilateral 4 nodes (QUA4), meanwhile for the steel reinforcement and the CFRP is linear element (SEG2).
The loadings on this model are vertical and horizontal loads. The vertical load is proper loading due to the actual mass (the mass of the upper sill and device) of 25000 kg. While, for the horizontal loading, the loading force and loading displacement are applied to the peak point of the shear wall in the horizontal direction.

5. RESULT AND DISCUSSION

A. Shear Walls T8

a. The Pushover Loading

i. The Force Imposed

The force is proportional to displacement. The maximum force is 348000 kg for a displacement of 0.58 cm. The minus sign indicates that the direction of force is opposite to the direction of the applied force imposed on the veil. Concrete is a material that is resistant to the compression but relative low to the traction. Therefore, the number of points affected by cracking is so much higher compared to compression.

![Fig. 3 Force and Displacement of Shear Walls T8](image-url)
The deformation is proportional to the displacement. The maximum strain of concrete is 0.00424 for a displacement of 0.58 cm. And for the reinforcement, the maximum strain is 0.00969 for a displacement of 0.441 cm.
ii. The Displacement Imposed

Fig. 7 Force and Displacement of Shear Walls T8

Fig. 8 Points Affected by Cracking and Compression

Fig. 9 Deformation of Concrete
The maximum force is 349000 kg for a displacement of 0.598 cm. The maximum strain of concrete is 0.00327 for a displacement of 0.526 cm. The deformation of vertical reinforcement is greater than horizontal reinforcement. This is because in this model, the horizontal force is more dominant than the vertical force. The reinforcement that holds the horizontal force (vertical reinforcement) undergoes greater deformation.

b. The Dynamic Loading

In T8_1, the largest displacement is about 0.3687 cm. In T8_2 and T8_3, the displacement increase significantly. The maximum displacement of T8_2 is about 0.527 cm, while the maximum displacement of T8_3 is about 0.7301 cm. The experimental results of T8_1, T8_2, and T8_3 are 0.2550 cm, 0.54 cm, and 1.09 cm.
For the effort in Fig. 12, the greatest effort of T8_1 is 279249 Kg. The greatest effort of T8_2 is 201029 Kg, while the greatest effort of T8_3 is 303932 Kg. The experimental results of T8_1, T8_2, and T8_3 are 224000 Kg, 329000 Kg, and 303932 Kg.

For the Fig. 13, the hysteresis curve T8_1 is unstable, because at the end of loading, there is a significant increase in force followed by an increase in displacement. In this T8_1, the shear wall cracks slightly. While on T8_2, the hysteresis curve is quite stable. But we can see here at the same time as increasing shear, there is also a significant increase in displacement. In this T8_2, the shear wall crack more heavily. And for the T8_3, it can be seen that the increase in effort is not too large, but the increase of the displacement is large enough.

B. Shear Walls T13

a. The Pushover Loading

i. The Force Imposed
The maximum force is 263759 Kg for a displacement of 0.29 cm. The number of points affected by cracking is much higher than in compression. In comparison with the shear walls T8, the number of points affected by cracking of shear walls T13 is much higher. It is due to the size of the mesh that is very fine.

Fig. 14 Force and Displacement of Shear Walls T13

Fig. 15 Points Affected by Cracking and Compression

Fig. 16 Deformation of Concrete
The maximum strain of concrete is 0.00226 for a displacement of 0.29 cm. The maximum strain of reinforcement is 0.00967 for a displacement of 0.29 cm.

ii. The Displacement Imposed

Fig. 18 Force and Displacement of Shear Walls T13

Fig. 19 Points Affected by Cracking and Compression
The maximum force is 344000 Kg for a displacement of 0.48 cm. The maximum strain of concrete is 0.00898 for a displacement of 0.48 cm. The maximum strain of reinforcement is 0.00967 for a displacement of 0.29 cm.

**Fig. 20 Deformation of Concrete**

**Fig. 21 Deformation of Reinforcement**

**b. The Dynamic Loading**

**Fig. 22 Displacement at The Top of Shear Walls T13**
In T13_1, the largest displacement is about 0.1 cm. In T13_2 and T13-3, the displacement increase significantly. The maximum displacement of T13_2 is about 0.57 cm, while the maximum displacement of T13_3 is about 0.9 cm. The experimental results of T13_1, T13_2, and T13_3 are 0.1 cm, 0.65 cm, and 1.5 cm.

For the effort in Fig. 23, we can see that in T13_1, the greatest effort is about 133000 Kg. In T13_2 and T13_2, the greatest effort are about 265000 kg and 300000 Kg.

Fig. 24 shows the ductile behavior of the structure and the damping capacity of the structure. Same with the experimental results, the hysteresis of T13_1 is stable. While in T13_2, the shear wall is cracking slightly. And for the T13_3, it can be seen that the increase in effort is not too large, but the increase of the displacement is large enough. In this T13_3, the shear wall is cracking and massively destroyed.

6. CONCLUSION

- The hysteresis curves of the test and the hysteresis curves of the numerical modeling approach each other.
The curve displacement-time of the test and the curve displacement-time of the numerical modeling approach each other.

If the mesh size used is smaller, the results will be more details.

The displacement of shear walls with CFRP is lower than the displacement of shear walls without CFRP.

7. REFERENCES


8. ACKNOWLEDGEMENTS

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