New Replaceable Coupling Beams for Shear Wall Structures

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SUMMARY
A kind of new coupling beams had been designed to be used for shear wall structures, and the common characteristics of the beam was that it could be replaced after earthquake damage. The new replaceable coupling beam was composed of elastic elements and sacrificial elements (may also called "fuse"). Elastic elements were made of steel reinforced concrete and sacrificial elements, whose shape was a steel I-beam with a diamond-shaped hole in middle cross. Due to the use of sacrificial high energy absorbing elements within these coupling beams, it could absorb and dissipate large amounts of energy prior to its failure. Also, since these sacrificial elements were connected to elastic elements by bolt, it could be easily replaced after damage. In order to study the seismic performance of new replaceable coupling beams before test, two coupled shear wall calculation models were built, of which one shear wall coupling beams was replaceable, the other was the conventional coupling beams. Comprehensive calculation analysis showed that the damage of the new replaceable coupling beams focused on the "fuse", even the elastic elements of the coupling beam keeping intact. In contrast, the destruction of conventional coupling beams focused on the end, and it is difficult to repair the damage. In addition, the four large half-scale models are being produced, to be tested to further study the seismic performance of the new coupling beams by cyclic loading test.

Keywords: replaceable coupling beams, elastic elements, sacrificial elements, push-over analysis

1. INTRODUCTION

Shear wall structures are most important lateral-force-resisting-systems that have been shown to be very efficient in resisting seismic loads. But previous earthquake damages showed that the coupling beams were easily damaged in the earthquake and it was often used as an energy dissipation part in structures. (shown as Fig. 1.1, Fig. 1.2). Especially, in 2/27/2010 Chile Magnitude 8.8 Earthquake, a large number of coupling beams were seriously damaged (Carpenter, Naeim, and Lew et al. 2011). Furthermore, it was difficult to repair these coupling beams after earthquake, and it would cause the building life-cycle cost increasing. So, it is necessary to transform traditional anti-collapse design approach to the repairable design method in some important structures. One of the simplest ways to achieve repairable design is to set some replaceable structural members in proper positions of a structure while the whole structure still works as an integrate system.

Previous study (Fortney, Shahrooz, and Rassati 2006, 2007) had investigated the behavior of replaceable fuse steel coupling beam by test and calculation. Research results showed that fuse steel coupling beam demonstrated well performance, but the fillet welds used in the built-up I-sections had been terminated at the ends of the beam sections, which led to the onset of the fillet weld failures. (shown as Fig. 1.3, Fig. 1.4). Similarly, the authors of this paper connected fuse with non-yield segment by end plate instead of splice plate in order to minimize the destruction of non-yield segment. In the paper, a new coupling beams "fuse" will be introduced, and design methodologies of new coupling beams had been developed. Finally, static push-over analysis studies was done to investigate the seismic performance of the new coupling beams. In addition, four large half-scale models of shear walls with the replaceable coupling beams has being produced, to be used to further study the seismic performance of the new coupling beams by cyclic loading test.

Figure 1.1. Photo for failure of coupling beam in 5/12/ 2008 wenchuan earthquake, China

Figure 1.2. Photo for failure of coupling beam in 2/27/2010 Chile Magnitude 8.8 earthquake

Figure 1.3. As-built details of replaceable coupling beams(Fortney, 2005)

Figure 1.4. The fuse torn through the web of the fuse(Fortney, 2005)

2. DESIGN METHODOLOGIES

New replaceable coupling beam design requirements (Lu, X. L., Mao, Y. J. and Chen, Y., 2012):

Under frequent earthquakes, the new replaceable coupling beam is the same as conventional coupling beam, supposed to provide stiffness to the system and keep intact; Under basic earthquake or rare earthquake, the fuse of new replaceable coupling beam should yield in advance and dissipate seismic energy, whereas the non-yield segment keeps elastic.

In order to unify with the design methods of conventional coupling beams, and to facilitate the structural designer to understand the new design method, new coupling beam design method is based on design methods of the conventional coupling beams. The specific design steps show as follows:

The first step, choose conventional coupling beams that should be substituted by replaceable coupling beams. However, the internal force calculation is still in accordance with conventional coupling beam. The second step, after obtaining the coupling beam shear and moment, there is no need to satisfy shear load ratio limits requirements. This is a very important advantage comparing with conventional coupling beams. Then, the bearing capacity calculation of new replaceable coupling beams was composed of two parts:

(1)The non-yield segment design

The design requirement is that the non-yield segment should not damage in any basic earthquake or rare earthquake. Therefore, the coupling beam calculation moment should multiply by the amplification factor μ, which is greater than 1, and then flexural bearing capacity calculation of the non-yield segment use the new moment. Similarly, the coupling beam calculation shear should multiply by the same amplification factor μ, and then shear bearing capacity calculation of the non-yield segment use the new shear. The value of μ is not easy to determine, in principle, a higher value can minimize the damage possibility of the non-yield segment, but a higher value may result in cost rising.

(2)The fuse design

The fuse design requirement is that the fuse should keep elastic under frequent earthquake, but it should yield in advance and dissipate seismic energy under basic earthquake or rare earthquake. Fuse design moment is the same as conventional coupling beam design moment, and flexural capacity calculation is based on the design moment. Also, the fuse design shear is the same as conventional coupling beam design shear. In this case, the fuse would yield under the design shear and dissipate energy under basic or rare earthquake.

The Fig. 2.1 is the design flowchart of new replaceable coupling beams (Lu, X. L., Mao, Y. J. and Chen, Y., 2012).

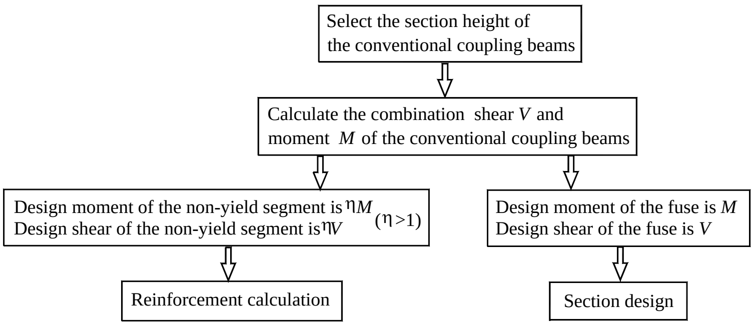

Figure 2.1. New coupling beam design flow chart

3. DESIGN EXAMPLES OF NEW REPLACEABLE COUPLING BEAMS

Because the test subassemblies are considered to be approximately ½ scale of a typical coupled core wall, so, the design method of new replaceable coupling beam was introduced according to Fig. 2.1 in section 2.

According to section 2, the section height of the conventional coupling beams should be determined firstly. Consequently, the author assumed that the section height of the conventional reinforced concrete coupling beams was 200mm, and the span of it was 600mm. its shear design value V_b was $24kN$ and moment design value M_b was $7.2kN$. Fig. 3.1 showed the schematic diagram of the new replaceable coupling beams.

Generally, the span of the new coupling beams should be the same as conventional coupling beams. So, the span of the new coupling beams was also 600mm, including two non-yield segments and one "fuse". The span and height of the non-yield segment were 200mm. The shape of "fuse" was a steel I-beam with a diamond-shaped hole in middle cross. According to Fig. 2.1, flexural bearing capacity and shear bearing capacity of the non-yield segment should be calculated and the "fuse" section should also be designed.

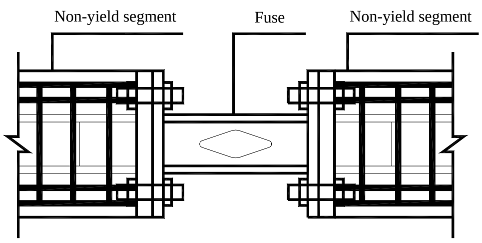

Figure 3.1. New coupling beams

The “fuse” section design:

According to Fig. 2.1, the internal force of “fuse” was the same as internal force of the conventional coupling beams. Because the “fuse” was a steel I-beam with a diamond-shaped hole in middle cross, so, the shear stress of the T section in the hole should be calculated in accordance with Eqn. 3.1:

$$\tau = \frac{VS_T}{2t_w I_T} \tag{3.1}$$

where： V is the shear in the hole section； t_w is the thickness of the web； S_T is the area moment of the T section; I_T is the moment of inertia.

The most dangerous cross section should be selected to calculate. In the middle of “fuse”, the web area was seriously weakened, so, the shear bearing capacity should be computed here. In contrast, the moment of “fuse” end was larger, so, the moment bearing capacity should be computed here. After preliminary calculations, then “fuse” cross section in the middle span was shown in Fig. 3.2.

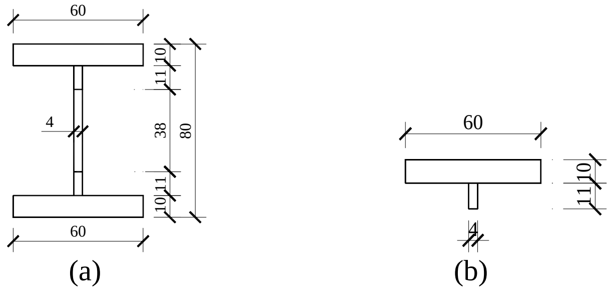

Figure 3.2. The cross section in the middle span of “fuse”

Moment bearing capacity of T-section shown as Fig. 3.2 (b) should be computed according to Eqn. 3.2～Eqn. 3.4:

$$I_T = \frac{1}{12}\times 60\times 10^3 + \frac{1}{12}\times 4\times 11^3 + 60\times 10\times (5.72-5)^2 + 4\times 11\times (10+5.5-5.72)^2 = 9963mm^4 \tag{3.2}$$

$$S_T = 4\times 11\times (10+11\times 0.5-5.72) = 430mm^3 \tag{3.3}$$

$$\tau = \frac{\gamma_{RE} VS_T}{2t_w I_T} = \frac{0.85\times 24\times 1000\times 430}{2\times 4\times 9963} = 110N/mm^2 < 125N/mm^2 \tag{3.4}$$

where： γ_{RE} is seismic adjusting coefficient for load-bearing capacity of the structural member.

Consequently, the shear bearing capacity meet requirement, and design shear stress was slightly less than yield stress. The moment bearing capacity checking of I section was ignored. The photo of the “fuse” was shown as Fig. 3.3.

Figure 3.3. Photo for “fuse”

Non-yield segment design：

Based on aforementioned design flow chart of new replaceable coupling beams, the design method of the non-yield segment include calculation of flexural bearing capacity and shear bearing capacity. Firstly, the moment design value and shear design value of the non-yield segment should be determined. Its design moment and design shear should multiply by a magnification factor η on the basis of internal force design value of conventional coupling beams. The η value should be related to the seismic level, so, here assumed 1.2 . The design shear of non-yield segment was $V_b = 1.2 \times 24 = 28.8kN$, and design moment was $M_b = 1.2 \times 7.2 = 8.64kN$.

Fig. 3.4 showed the reinforcement of non-yield segment, whose moment bearing capacity checking did not consider the contribution of I steel.

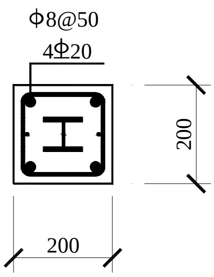

Figure 3.4. The reinforcement of non-yield segment **Figure 3.5.** Photo for embedded steel

According to《Code for Seismic Design of Buildings》(Chinese) and《Code for Design of Concrete Structures》(Chinese), Eqn. 3.5～Eqn. 3.6 can be obtained:

$$M \le f_y A_S \left(h - a_s - a_s^{'} \right) / \gamma_{RE} \tag{3.5}$$

$$8.64kN \le 300 \times 3.14 \times 2 \times 10^2 \times \left(200 - 25 - 25 \right) / 10^6 = 28.26kN \tag{3.6}$$

where $\gamma_{RE} = 0.75$ ， $a_s = a_s^{'} = 25mm$.

Consequently, the moment bearing capacity of the non-yield segment meet requirement.

Generally, the shear force of the non-yield segment was borne by the concrete and stirrups, but the contribution of embedded steel should be considered according the actual situation. Here, the cross section of embedded steel was the same as “fuse” to connect easily.

According to《Technical Specification for Steel Reinforced Concrete Composite Structures》(Chinese), Eqn. 3.7～Eqn. 3.8 can be obtained:

$$V_b \le \frac{1}{\gamma_{RE}} \left[0.06 f_c b h_0 + 0.8 f_{yv} \frac{A_{sv}}{s} h_0 + 0.58 f_a t_w h_w \right] \tag{3.7}$$

$$28.8 \le \frac{1}{0.85} \left[0.06 \times 11.9 \times 200 \times 175 + 0.8 \times 210 \times \frac{3.14 \times 4^2 \times 2}{50} \times 175 + 0.58 \times 215 \times 4 \times 60 \right] / 10^6 = 134kN \tag{3.8}$$

Consequently, the shear bearing capacity of non-yield segment meet requirement, and the photo of the embedded steel showed as Fig. 3.5.

4. ANALYTICAL STUDY

4.1. Computational model

In order to verify the previous design method and compare the seismic performance between new coupling beams and conventional coupling beams, two finite element models were established. The first one is a shear wall with conventional coupling beams, while the other is a shear wall with new replaceable coupling beams. The model geometric design parameters were shown as Fig. 4.1. The size and reinforcement of two shear walls are exactly the same except reinforcement of coupling beams.

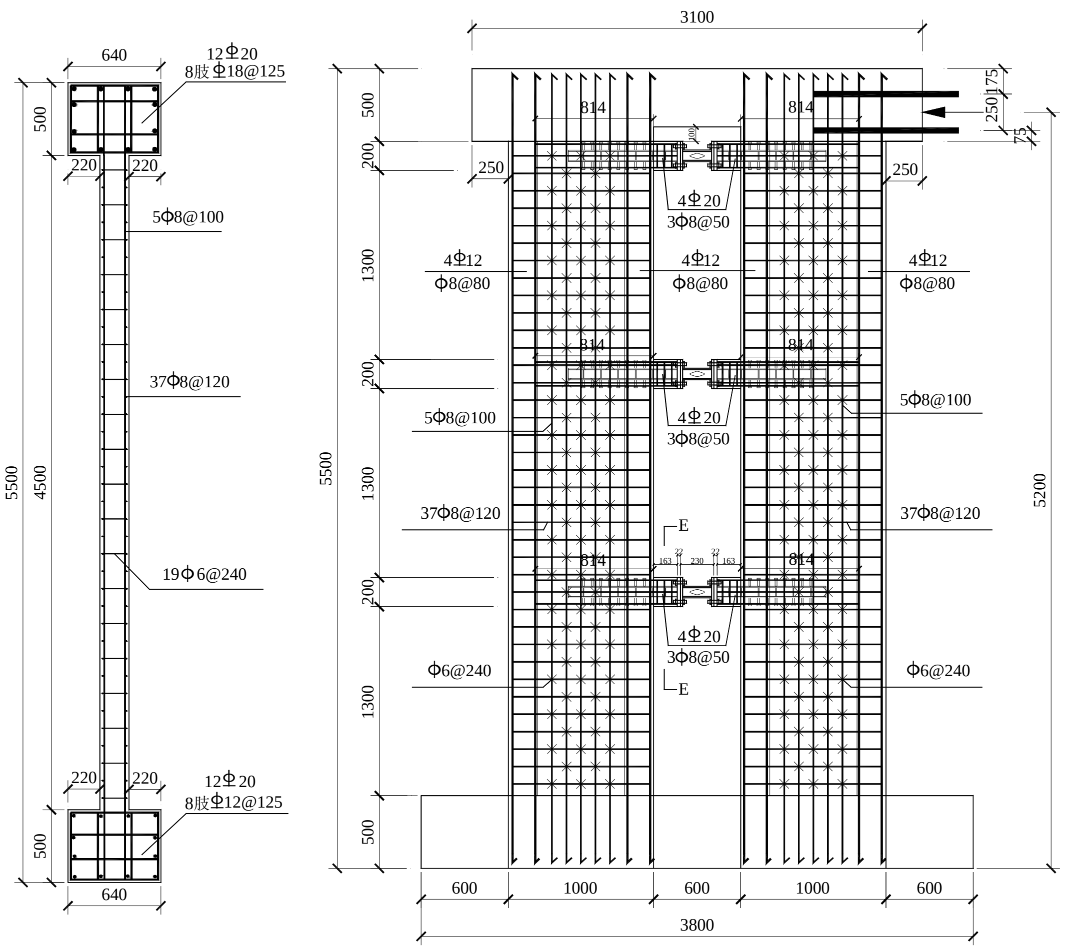

Figure 4.1. Reinforcement of new shear wall with replaceable coupling beams

The fuse was Q235 steel with yield strength of 235MPa. Solid 65 elements were used to simulate concrete, and shell 181 element was utilized in the modeling of “fuse”. Reinforcement was modeled by pipe20 element. All used steel and reinforcement were assumed to behave as ideal elastic plastic material. The shear wall with replaceable coupling beams finite element model was shown in Fig. 4.2.

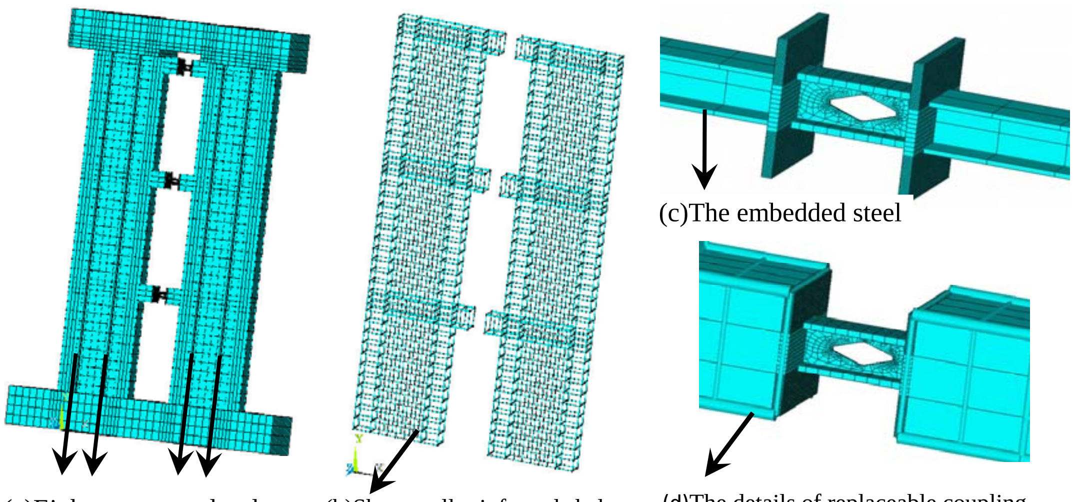

Figure 4.2. The shear wall with replaceable coupling beams

4.2. Static push-over analysis

For a detailed comparison of the seismic performance between conventional shear wall and new shear wall, a static push-over analysis was carried out. An axial load of 1600kN was first applied by prestressed rod until the axial-force-ratio reached 0.28. Then, displacement controlled load was applied until inter-story drift angles of both shear wall reached approximately 1/50. The base shear-top displacement curves obtained from the analysis were shown in Fig. 4.3 and Fig. 4.4.

As was shown in Fig. 4.3 and Fig. 4.4, the conventional shear wall and new shear wall have similar change process of force. Moreover, these two graphs expressed the yield order of shear wall components. In conventional shear wall, the longitudinal rebar of coupling beams first yielded, then, the longitudinal rebar of boundary element began to yield. Finally, the whole structure yielded. Similarly, in new shear wall, the "fuse" web first began to yield, then, the longitudinal rebar of boundary element began to yield. Finally, the whole structure yielded.

However, the yield mechanisms of the two coupling beams were very different. The fuse of new coupling beam generated shear deformation yield, but the longitudinal rebar of non-yield segment did not yield. In contrast, longitudinal rebar of conventional coupling beams yielded and concrete generated shear failure generally, which is difficult to repair after earthquake. The deformation and von mises of two coupling beams were shown as in Fig. 4.5 ～Fig. 4.8.

From Fig. 4.5 and Fig. 4.7 can be seen, the replaceable coupling beams mainly produced shear deformation and its deformation focused on the "fuse", while the conventional coupling beams mainly produced flexural deformation and its end curvature was the largest. So, Fig. 4.6 showed the most of "fuse" web had yielded, but embedded I steel of non-yield segment was still in the elastic state.

Although all of the longitudinal rebar had yielded in conventional coupling beams, maybe this was useful for coupling beams to dissipate earthquake energy. It should be noted because span to depth ratio of the conventional coupling beams was bigger in this article, so flexural deformation was major. But the actual situation was that span to depth ratio of most coupling beams was small, so, the coupling beams often generate shear failure, which was harmful to the structure.

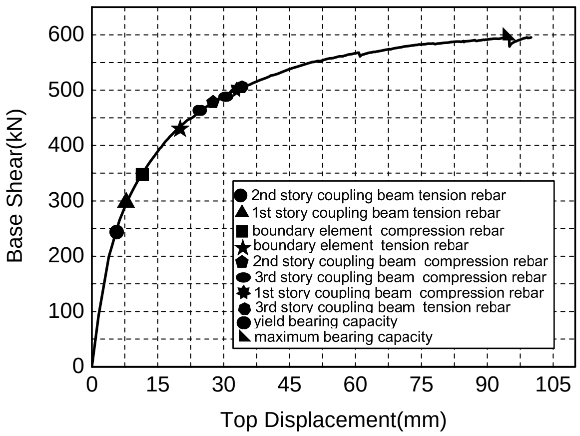

Figure 4.3. Base shear-top displacement curves of conventional shear wall

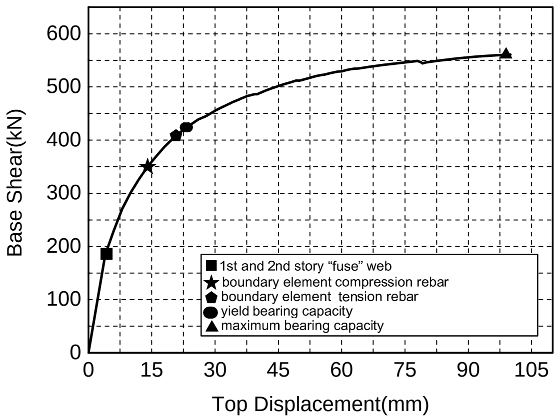

Figure 4.4. Base shear-top displacement curves of shear wall with replaceable coupling beams

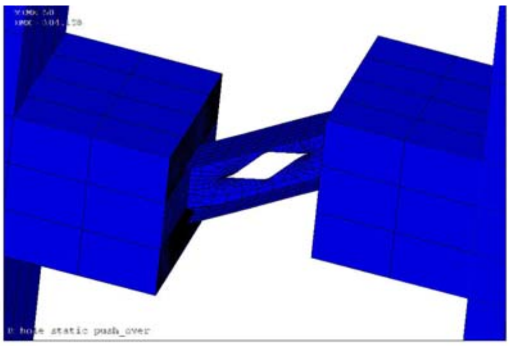

Figure 4.5. The deformation of replaceable coupling beams

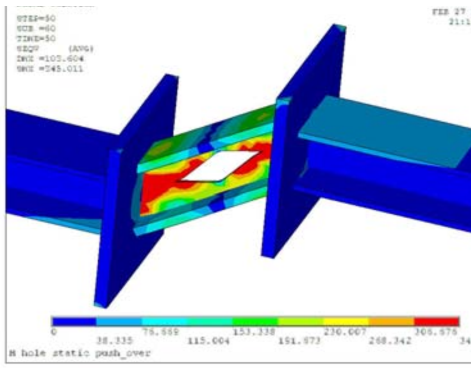

Figure 4.6. The von mises of "fuse"

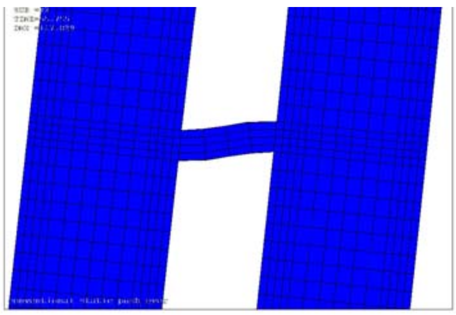

Figure 4.7. The deformation of conventional coupling beams

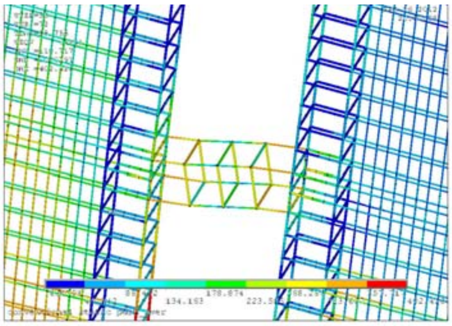

Figure 4.8. The von mises of steel rebar of conventional coupling beams

By comparing Fig. 4.9 and Fig. 4.10 can be seen, the compression wall would bear more shear than tension wall. Particularly the shear of the compression wall was nearly three times than tension wall in conventional shear wall, which indicated the conventional coupling beams afford more constraint moment to the wall limbs. In contrast, the shear of the compression wall was a little bigger than tension wall in new shear wall, which indicated the replaceable coupling beams afforded weak constraint moment to the wall limbs. Because the wall limbs size of two shear wall was the same, so, the bearing capacity of replaceable coupling beams was weaker than the conventional coupling beams.

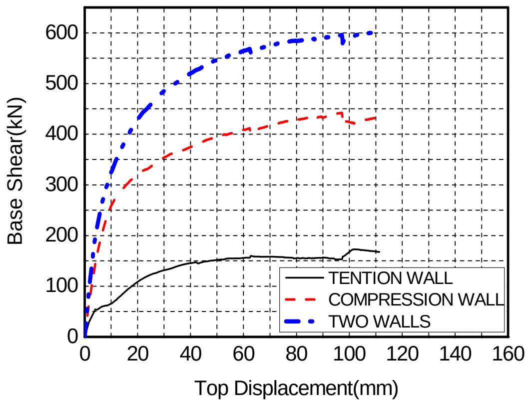

Figure 4.9. Base shear-top displacement curves of conventional shear wall

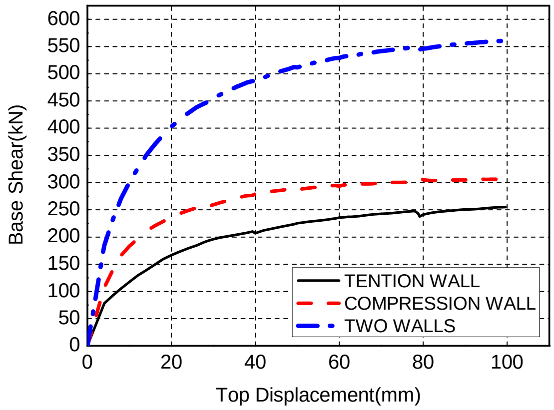

Figure 4.10. Base shear-top displacement curves of shear wall with replaceable coupling beams

By comparing Fig. 4.11 and Fig. 4.12, the difference was that the compression wall of conventional shear wall beard more axial force than new shear wall, and the tension wall of conventional shear wall beard less axial force than new shear wall. This further indicated that the bearing capacity of conventional coupling beams was bigger than replaceable coupling beams.

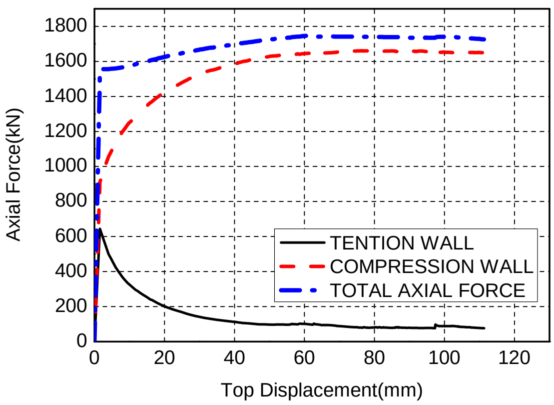

Figure 4.11. Axial force-top displacement curves of conventional shear wall

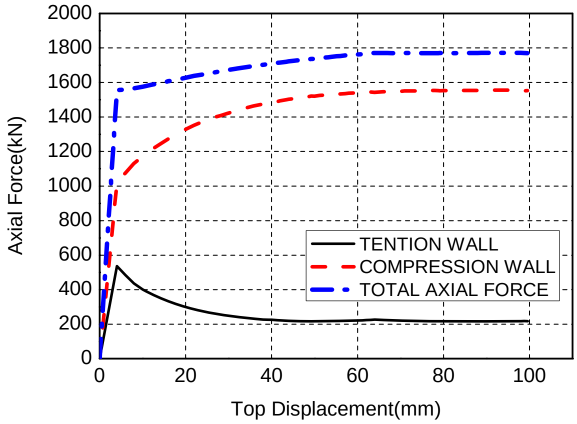

Figure 4.12. Axial force-top displacement curves of shear wall with replaceable coupling beams

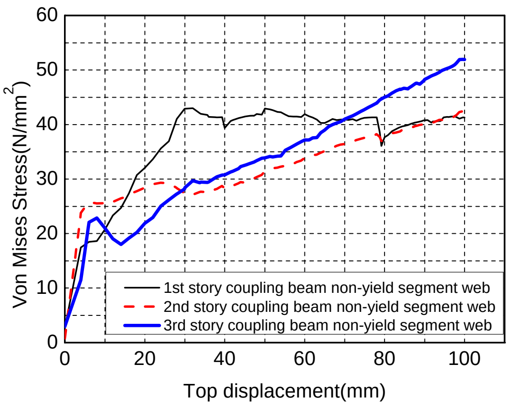

Figure 4.13. Von mises stress of non-yield segment web

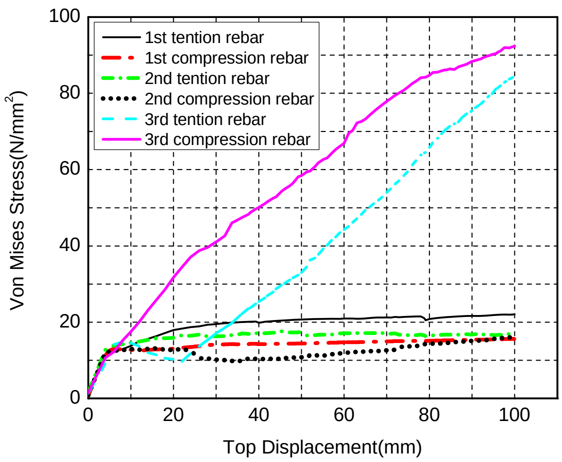

Figure 4.14. Von mises stress of longitudinal rebar of replaceable coupling beams

Fig. 4.13 and Fig. 4.14 showed the von mises stress of longitudinal rebar and non-yield segment web in replaceable coupling beams, that can be found all of the stress was less than the yield strength, so the non-yield segment keep elastic. In this case, it is convenient to replace “fuse” in pose-earthquake.

5. SUMMARY AND CONCLUSIONS

This article focuses on new shear wall with replaceable coupling beams and conventional shear wall, comparing the mechanical properties by numerical simulation, and the following preliminary conclusions were drawn:

1. The design method of replaceable coupling beams was proposed, and a detailed design example was given.

2. The numerical simulation demonstrated the damage can be concentrated in the “fuse” of the replaceable coupling beam, while the remaining parts of the coupling beam kept elastic. This was beneficial to repair after earthquake.

3. In this article, because the design internal force of conventional coupling beams was more than replaceable coupling beams, constrain moment of conventional coupling beams was also more than replaceable coupling beams, which was verified by calculation.

4. Another advantage of replaceable coupling beams was that it may not need to satisfy shear load ratio limits requirements, because the failure modes was controlled by the “fuse”. Although “fuse” would shear yield, it still will provide constrain moment to wall limbs. In contrast, when the conventional coupling beams began to shear failure, it would not afford any constrain moment to the wall limbs and would not dissipate any earthquake energy. It should be noted that this did not be verified in the analysis, for the span to depth ratio of conventional coupling beams was larger, maybe it would not produce shear failure.

5. The four large half-scale models are being produced, to be tested to further study the seismic performance of the new coupling beams by cyclic loading test, maybe more useful and interesting conclusions will be discovered in the test.

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