SIMPLIFIED DESIGN METHOD OF FRAME WALL BEAM OF COMPOSITE WALL BUILDINGS SUPPORTED ON FRAME

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Wu Ruiduo³  Xi Xiaofeng³  Jie Mingyu³

1. ABSTRACT

The frame wall beam is an important bearing member. The quality of design is related to safety and economy of the buildings. Based on experimental study and theoretical analysis of the stress state of frame wall beam, a simple, applicable, safe and economic design method is developed in this paper.

2. INTRODUCTION

The structure of composite wall supported on frame is the new structure system studied and developed in 1990s, suitable for the commercial resident buildings with big space in the lower part and small bay in the upper part. During eighth five years plan, the composite wall buildings of million square meters were built in Shenyang only. It takes important rules in promoting economic prosperity, convenience for the people, The great economic effect was obtained. The frame wall beam is the beam of frame at the top of frame supported story in composite wall with framed first story, it is an important member. It is used to be designed as flexural member or wall beam. The methods determining the value of loads in the previous design methods were lack of experimental and theoretical basis. The simplified calculation method in Chinese Code for Design of Masonry Structures is not suitable for continuous wall beam, still for wall without confined columns and seismic region.

Keyword: Simplified Method; Frame Wall Beam; Composite Wall Supported on Frame.

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Based on research on stress state of frame wall beam, a simple, applicable, economic and safe design method is proposed in this paper.

3. MECHANICAL PROPERTIES

The frame wall beam is the beam of frame at the top of frame supported story in composite wall with framed first story, being the joining part of two different structures, the position of the frame wall beam is shown in Fig. 1. The frame wall beam is different from nor the beam of frame or common wall beam, The properties of the frame wall beam are as follows:

![Fig. 1 the position of frame wall beam](image)

1. The reinforced concrete frame-shear wall structure is at the lower part of the frame wall beam, the upper part is the reinforced concrete-brick composite wall structure;
2. There are confined columns in wall above the frame wall beam, the confined columns bear forces together with masonry;
3. A part of vertical load above the frame supported story is directly passed to the columns of the frame through confined columns, the other through interior arch effect of masonry, reducing vertical forces on the frame wall beam;
4. Under the vertical load or both the vertical and horizontal load, the frame wall beam bears bending, shear and axial forces.
4. EXPERIMENTS

Six \( \frac{1}{2} \) scale frame supported composite wall panel models were tested, i.e., two transverse composite wall models with frame supported first story (with and without opening, as shown in Fig. 2), two transverse composite wall models with frame supported first two stories (with and without opening, as shown in Fig. 3), one longitudinal composite wall model with frame supported first story (four bays with opening, as shown in Fig. 4), one longitudinal composite wall model with frame supported first two stories (four bays with opening, as shown in Fig. 5). Only four stories of the bottom of eight-story composite wall with frame supported were selected for the above wall panel models. But the models were used to simulate the behavior of the eight-story composite wall with frame supported.
The experimental results showed:

(1) The stress states of the transverse frame wall and longitudinal frame wall beam with no opening or small-sized opening are similar to that of wall beam. The stress state of midspan of the beam is eccentric compression, the stress state near the support is eccentric tension, mainly flexure. The arch effect of upper composite wall above the exterior longitudinal frame wall beam with bigger opening is not significant. Its stress state is similar to that of multi-span continuous beam.

(2) The load applied on the frame wall beam is distributed in shape of saddle. The load in the support is great, the load in the midspan is small. There are loads varying along the axial of the beam in the transverse frame wall beam, the stress in the midspan is tensile, the stress in the support is compressive.

(3) Total loads passed from upper composite wall are mainly passed to the column of frame by confined columns and through the arch effect of composite wall above the beam of frame wall, only a little part is passed to the column of frame through the frame wall beam. As the result, the frame wall beam does not bear great vertical load. Even if the beam is under action of horizontal force, the beam bears less than 45% total load, see Table 1.

(4) The beam of transverse frame wall out of the confined column, local vertical load in the edge of opening increases a little.

**Table 1** the proportion of vertical loads borne by frame wall beam

<table>
<thead>
<tr>
<th>Type of wall panel</th>
<th>composite wall with frame supported first story</th>
<th>composite wall with frame supported first two story</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V</td>
<td>V+ (7°)</td>
</tr>
<tr>
<td>transverse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>with no opening</td>
<td>23.9</td>
<td>28</td>
</tr>
<tr>
<td>with opening</td>
<td>32.6</td>
<td>35.7</td>
</tr>
<tr>
<td>longitudinal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Window opening</td>
<td>24.5</td>
<td>32.6</td>
</tr>
</tbody>
</table>
where

\[ V \] — only vertical load

\[ V + 7^0 \] — vertical load and horizontal force corresponding to earthquake of intensity VII

\[ V + 8^0 \] — vertical load and horizontal force corresponding to earthquake of intensity VIII

5. **NONLINEAR FINITE ELEMENT ANALYSIS**

The composite wall with frame supported first (two) story of eight-story building was analyzed by plane nonlinear finite element method. The parameters used in the analysis are as follows:

- **concrete strength grade:**
  - C30 for columns of frame, C30 for beams of frame, C20 for confined columns.

- **opening in transverse composite wall:**
  - no opening, opening in one side of middle column;
  - openings in two sides of middle column, openings in exterior side of mid-column in the side.

- **opening in longitudinal composite wall**
  - 1500 × 1500, 1800 × 1500,
  - 900 × 2000+1200 × 1500 (door and window).

- **installation of interior confined columns on the transverse frame wall beam**
  - no confined column (as shown in Fig.6), only confined columns at the two ends of wall (as shown in Fig.7), confined columns at the two the ends and middle of wall (as shown in Fig.8), two columns in addition to side and middle columns (as shown in Fig.9).

![Fig.6 no confined column on the transverse frame wall beam](image1)

![Fig.7 only confined columns at the two ends of wall](image2)
Fig. 8 confined columns at the two the ends and middle of wall

Fig. 9 two columns in addition to side and middle columns

- section size of beam of frame:
  \(400 \times 400, 500 \times 500, 600 \times 600\)
- section size of confined column:
  For side and middle columns: \(240 \times 300, 240 \times 400, 336 \times 400\),
  For middle columns in the side: \(450 \times 600, 450 \times 800\).
- section size of beam of frame wall:
  transverse frame wall beam: \(300 \times 600, 300 \times 800, 300 \times 1000, 450 \times 600, 450 \times 800\),
  longitudinal frame wall beam: \(250 \times 300, 300 \times 350, 300 \times 450\).
- bay size:
  \(3300, 3600, 4200, 5400\).
- depth size:
  \(5100, 5700, 6300\).

The results are given in Table 2.

<table>
<thead>
<tr>
<th>opening</th>
<th>number of openings</th>
<th>side column frame wall beam</th>
<th>middle column frame wall beam</th>
<th>side column frame wall beam</th>
<th>Σ frame wall beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>no</td>
<td>0</td>
<td>24.4</td>
<td>14.5</td>
<td>22.2</td>
<td>14.5</td>
</tr>
<tr>
<td>one in side of middle column</td>
<td>1</td>
<td>25.4</td>
<td>15.0</td>
<td>21.9</td>
<td>12.6</td>
</tr>
<tr>
<td>one in two sides of middle column</td>
<td>2</td>
<td>26.2</td>
<td>12.9</td>
<td>21.8</td>
<td>12.9</td>
</tr>
<tr>
<td>exterior side of middle column in side</td>
<td>1</td>
<td>24.3</td>
<td>15.0</td>
<td>23.6</td>
<td>13.4</td>
</tr>
</tbody>
</table>
Table 3  Distribution of vertical force when installing different confined column under vertical load

<table>
<thead>
<tr>
<th>number of columns</th>
<th>section size of column</th>
<th>strength of masonry</th>
<th>side column</th>
<th>frame wall beam</th>
<th>middle column</th>
<th>frame wall beam</th>
<th>side column</th>
<th>∑ frame wall beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>400 × 240</td>
<td>M10</td>
<td>25.0</td>
<td>13.3</td>
<td>23.4</td>
<td>13.3</td>
<td>25.0</td>
<td>26.6</td>
</tr>
<tr>
<td>5</td>
<td>300 × 240</td>
<td>M10</td>
<td>24.6</td>
<td>17.3</td>
<td>16.2</td>
<td>17.3</td>
<td>24.6</td>
<td>34.6</td>
</tr>
<tr>
<td>5</td>
<td>400 × 240</td>
<td>M10</td>
<td>24.4</td>
<td>14.5</td>
<td>22.2</td>
<td>14.5</td>
<td>24.4</td>
<td>29.0</td>
</tr>
<tr>
<td>5</td>
<td>400 × 240</td>
<td>M7.5</td>
<td>24.6</td>
<td>14.0</td>
<td>22.8</td>
<td>14.0</td>
<td>24.6</td>
<td>28.0</td>
</tr>
</tbody>
</table>

Table 4  Influence of change in size on distribution of vertical force

<table>
<thead>
<tr>
<th>section size</th>
<th>side column + middle column</th>
<th>middle column in the side</th>
<th>masonry</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam of frame</td>
<td>stiffness (%)</td>
<td>vert. force (%)</td>
<td>stiffness (%)</td>
</tr>
<tr>
<td>400 × 400</td>
<td>49.7</td>
<td>67.9</td>
<td>23.6</td>
</tr>
<tr>
<td>500 × 500</td>
<td>49.7</td>
<td>67.1</td>
<td>23.6</td>
</tr>
<tr>
<td>600 × 600</td>
<td>49.7</td>
<td>66.5</td>
<td>23.6</td>
</tr>
</tbody>
</table>

Table 5  Influence of change in section of beam of frame and confined column on vertical force

<table>
<thead>
<tr>
<th>Spec. No.</th>
<th>section size of beam</th>
<th>side column</th>
<th>mid. column</th>
<th>beam in the side</th>
<th>masonry</th>
<th>vert. force (%) on beam (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1</td>
<td>0.45 × 0.6</td>
<td>0.336 × 0.4</td>
<td>71.69</td>
<td>0.24 × 0.4</td>
<td>7.27</td>
<td>21.04</td>
</tr>
<tr>
<td>SC2</td>
<td>0.45 × 0.8</td>
<td>0.336 × 0.4</td>
<td>67.1</td>
<td>0.24 × 0.4</td>
<td>10.45</td>
<td>22.45</td>
</tr>
<tr>
<td>SC4</td>
<td>0.45 × 0.6</td>
<td>0.336 × 0.4</td>
<td>72.18</td>
<td>0.24 × 0.3</td>
<td>5.93</td>
<td>21.89</td>
</tr>
<tr>
<td>SC5</td>
<td>0.45 × 0.8</td>
<td>0.336 × 0.4</td>
<td>67.84</td>
<td>0.24 × 0.3</td>
<td>8.54</td>
<td>23.62</td>
</tr>
<tr>
<td>SC7</td>
<td>0.45 × 0.6</td>
<td>0.24 × 0.4</td>
<td>65.42</td>
<td>0.24 × 0.4</td>
<td>8.81</td>
<td>25.77</td>
</tr>
<tr>
<td>SC8</td>
<td>0.45 × 0.8</td>
<td>0.24 × 0.4</td>
<td>60.52</td>
<td>0.24 × 0.4</td>
<td>12.46</td>
<td>27.02</td>
</tr>
<tr>
<td>SC10</td>
<td>0.45 × 0.6</td>
<td>0.24 × 0.4</td>
<td>65.93</td>
<td>0.24 × 0.3</td>
<td>7.21</td>
<td>26.86</td>
</tr>
<tr>
<td>SC11</td>
<td>0.45 × 0.8</td>
<td>0.24 × 0.4</td>
<td>61.28</td>
<td>0.24 × 0.3</td>
<td>10.22</td>
<td>28.50</td>
</tr>
</tbody>
</table>

The results of calculation and analysis showed:

1. The number of confined columns in upper wall has relatively great influence on the stress state of the frame wall beam. The vertical load passed to the frame wall beam through the wall without confined columns is 69% total vertical load. When the confined columns are installed at two ends of wall, the vertical load on the frame wall beam is 36% total load. When confined columns are installed at two ends and middle of wall, the vertical load on the frame wall beam decreases to 36% total load. When confined columns are installed not only at the two ends and middle of wall but also at the mid-span, the vertical load on the frame wall beam is slightly higher than one for three confined columns.

2. The proportion of vertical load borne by the frame wall beam increases with stiffness of the frame wall beam, decreases with increasing of openings in upper wall.

3. The change in section size of column of frame has little influence on the proportion of vertical load borne by the frame wall beam.

4. The proportion of vertical load borne by the frame wall beam under earthquake of intensity VII, VIII is the same as that under only the vertical load.

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6. SIMPLIFICATION OF INTERNAL FORCE CALCULATION FOR THE FRAME WALL BEAM

Under the action of vertical load or vertical and horizontal load, there are moments, shear and axial forces in section of beam of frame wall (see Fig.6 and Fig.10). Where the moments and shear forces are produced by vertical load applied on the frame wall beam. Though the vertical load is distributed in shape of saddle the internal force is the same as that in common beam with positive moment at midspan and relatively small shear force, with negative moment at support and relatively big shear force. The axial force is produced by arch effect of wall, being tensile at midspan and compressive at support. Obviously, the beam is under eccentric compression in support, eccentric tension at midspan. When designing project, the internal force computation and the verification of section bearing capacity are rather complex and difficult if finite element method is not used. For sake of requirements, simplification is as follows:

Fig.10 Internal force in frame wall beam under the load

(1) The results of finite element analysis indicated that moments and axial forces produce normal stress on the section of frame wall beam. The stress produced by axial forces is about 15% that by moments. The moment is control internal force of section capacity of the frame wall beam. The reinforcement can be determined by appropriately increasing maximum design value of moment to meet requirements for the simultaneous action of additional axial force. So it is necessary to calculate neither axial force nor reinforcement by eccentric tensile or compressive member.

<table>
<thead>
<tr>
<th>Table 6</th>
<th>The internal force in section of the beam of frame wall under different loads</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Section number</td>
<td>1</td>
</tr>
<tr>
<td>Vertical, shear force</td>
<td>-184.5</td>
</tr>
<tr>
<td>No action of shear force</td>
<td>-185.3</td>
</tr>
<tr>
<td>Vertical, shear force</td>
<td>-181.8</td>
</tr>
<tr>
<td>Moment opening</td>
<td>-188.9</td>
</tr>
</tbody>
</table>
Note: 1, The example is an actual project, which has a frame shear wall in first story and are reinforced concrete composite wall in upper seven stories.

2, The bay of the project is 3.30m, the depth is 3.10m.

(2) The loads distributed in shape of saddle on the frame wall beam are converted into uniformly distributed load by the principle of maximum moment equivalent. It is easy to calculate the internal forces (moment, shear force) by uniformly distributed load.

(3) Under only vertical force, the shear force applied at the top of the frame wall beam can be equilibrium itself. The shear force which has little influence on the moment can be ignored.

(4) The constructional requirements was met.

7. THE APPROXIMATE CALCULATING METHOD

As discussed in part 6, the internal force and bearing capacity of the section can be calculated by uniformly distributed load applied on the frame wall beam. It is the key to determine the uniformly distributed load reasonably. Based on the nonlinear finite element analysis and comparison analysis, the approximate calculating method was proposed.

(1) According to following Eq. (7.1.1), the uniformly distributed vertical load applied on the transverse frame wall beam is approximately computed as
\[ q''_E = 15(0.48 - 0.45 \frac{E_c A_c}{\sum E_i A_i} + 0.21 \times 10^{-3} E_c J_c) \frac{Q''}{L''_o} \]

where
\( q''_E \) — uniformly distributed vertical load applied on the transverse frame wall beam,
\( \sum E_i A_i \) — the sum of axial compressive stiffness of side and middle columns,
\( \Sigma E_i A_i \) — total axial compressive stiffness of composite wall,
\( E_c J_c \) — the bending stiffness of the frame wall beam (\( E_c \) in Mpa, \( J_c \) in m\(^4\)),
\( Q'' \) — the sum of vertical loads above the beam of transverse frame wall,
\( L''_o \) — the net span of the beam of transverse frame wall,
The above formula is also suitable for the interior and exterior longitudinal frame wall beam with openings less than 1000mm.

According to following Eq. (7.2.1), the uniformly distributed vertical load applied on the longitudinal frame wall beam is approximately computed as:

\[ q''_E = 12(0.5 - 0.387 \frac{E_c A_c}{\sum E_i A_i}) \cdot Q'' / L''_o \]

where
\( q''_E \) — uniformly distributed load applied the longitudinal frame wall beam,
\( E_c A_c \) — the sum of compressive stiffness of confined columns,
\( \Sigma E_i A_i \) — the sum of compressive stiffness of masonry and confined columns,
\( Q'' \) — the sum of vertical loads above the longitudinal frame wall beam,
\( L''_o \) — the net span of longitudinal frame wall beam.

8. SIMPLIFIED CALCULATION OF THE FRAME WALL BEAM

(1) to calculate the sum of vertical loads above the frame wall beam;
(2) to calculate uniformly vertical load borne by the transverse and longitudinal frame wall beam by Eq. (7.1.1) and (7.2.1), respectively.
(3) to calculate the internal forces (M, V) of the transverse and longitudinal frame wall beam by the method used for continuous beam;
(4) to check bearing capacity of cross section as flexural member;
(5) the frame wall beam shall comply with the following constructional requirements:

- The longitudinal tension or compression reinforcement of the beam should not have joints. If any, Welded joint should be used, and the area of reinforcement in joint should be not less than 25% the area of total reinforcements in the same section;
- Not less than 50% the upper negative moment reinforcements should be extended over the full length of the beam. The lower positive moment reinforcements should be extended to the column and anchored with the column;
- The waist reinforcement should be installed along the height of the beam. The waist reinforcements in the longitudinal frame wall beam should not be less than 2 φ 12, ones in the transverse frame wall beam should not be less than 2 φ 14, the spacing not more than 250mm;

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• The main and waist reinforcements should be anchored as tension reinforcements;
• The diameter of stirrups in the frame wall beam should be less than 8mm, the spacing not more than 200mm;
• The spacing of the stirrups in the region of 1.5 times beam height at the end of the beam and in the region of the door openings of the transverse frame wall beam and 500mm far from the edge of opening should be less than 100mm;
• Not less than 2 φ 16 ceiling reinforcements should be installed in the mid-column at the side of transverse frame wall beam.

9. CONCLUSIONS

(1) The frame wall beam is the beam of frame at the top of frame supported story in composite wall with framed first story, being the joining part of two different structures, it is a key bearing member in such structures. Based on the experimental study and theoretical analysis, the approximate calculation formula for design of the frame wall beam, simplified calculation method and seismic constructional measures are proposed.

(2) It is not only safe and reliable to use the methods presented in this paper for design of the frame wall beam, but also capable of saving the main materials, in designing a same beam of frame wall, about 28.6% concrete can be saved, longitudinal reinforcements 23.8%, stirrup 48.9%.

(3) Design methods proposed in this paper can still be extended to design of the beam analogous to the frame wall beam.

REFERENCES


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