Analysis and Computer Dynamic Three-Dimensional Model of Seismic Measures for High Rise Steel Frame Structure Using Finite Element Software

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Abstract. The newly-built 20-story hospital building is located in the seismic fortification 8 degree area, and its independent steel corridor is a steel frame structure. In order to analyze the performance of the structure under strong earthquake, the static and dynamic elastoplastic three-dimensional finite element model of the structure is established by using the finite element software PERFORM-3D. In this paper, buckling restrained braces are used for energy dissipation. Through the dynamic elastic-plastic analysis of the steel frame buckling restrained brace structure, the structural response under strong earthquake input is analyzed, and the structural reliability is checked.

Keywords: High intensity fortification area, Steel frame structure, Buckling restrained braces, Energy dissipation and shock absorption, Dynamic elastoplastic analysis.

1. Introduction

"Classification Standard for Seismic Fortification of Construction Engineering" Article 3.0.2 divides construction projects into four seismic fortification categories. Among them, the key fortification categories are: lifeline-related buildings that cannot be interrupted or need to be restored as soon as possible during an earthquake, and the consequences of major disasters such as a large number of casualties during an earthquake. The medical building serves a special group of patients and is a lifeline project. In the earthquake, we should not only ensure that it will not collapse, but also ensure the normal use of the medical function of the hospital. In this paper, the overall seismic performance and member deformation level of the steel corridor structure of the hospital project under construction are analyzed to provide analysis methods for similar projects.

The evaluation of the overall performance will be based on the displacement angle between elastic and plastic layers, the plastic development process and the plastic development area.

The evaluation of components evaluates the structure from the relationship between the plastic deformation of the component and the limit value of plastic deformation, the key parts, and the plastic deformation of the key components to ensure that the structural components are still able to withstand
the vertical seismic force and gravity during the earthquake. After the earthquake, the structure can still bear the gravity load acting on the structure. So as to ensure that the structure does not cause serious damage or collapse due to the damage of local components.

2. Project overview

New hospital project with a total construction area of about 130,000 square meters. Among them, the steel corridor IplI has 2 floors underground and 20 floors above ground. The standard floor height is 12.0m, and the total height of the structure is 85.35m. The structural system is steel frame buckling restrained brace structure.

The seismic fortification intensity of the project building is 8 degrees, and the designed service life of the structure is 50 years. The seismic fortification of the project building is classified as the key fortification class (Class B), and the designed basic seismic acceleration is 0.2g. The design earthquake group is divided into the third group, and the site category is Class II. The maximum value of horizontal earthquake influence coefficient is 0.16 for most earthquakes, and the maximum acceleration of time history analysis is 70gal for most earthquakes. The wind load carrier type coefficient is 1.3, and the basic snow pressure is 0.15kN/m². The ground roughness is Class C.

After the multi wheel optimization adjustment of the number and position of the supports, the final damping scheme is determined. The specific distribution quantity of each layer of the supporting layout scheme of the project is shown in the table below.

| Supp ort model | Material grade | Equivalent cross section (diameter mm) | Initial stiffness kN/mm | Stiffness after yield kN/mm | Yield load kN | Ultimate load kN | Yield displacement 10-3mm | Ultimate displacement 10-3mm | Connection method | Number |
|----------------|----------------|----------------------------------------|-------------------------|-----------------------------|---------------|------------------|---------------------------|---------------------------|-----------------|--------|
| BRB 1          | Q235           | 100                                    | 1.57X106/L              | 0.785X105/L                | 1500          | 2250             | 0.55L                     | 25L                       | Weld            | 40     |

Table 2. Support arrangement position

| Number of layers | X direction | Y direction |
|------------------|-------------|-------------|
| 1                | 4           | 4           |
| 2                | 4           | 4           |
| 3                | 4           | 4           |
| 4                | 4           | 4           |
| 5                | 4           | 4           |
| Total            | 20          | 20          |

3. Establishment of analytical model

3.1. Computing software

The establishment of a reliable analysis model is the basis for structural static and dynamic analysis. A reliable analysis model should first truly reflect the dynamic characteristics of the structure, and be able to analyze the static and dynamic responses of the structure in the elastic and elastoplastic phases relatively accurately. In order to analyze the performance of the structure under large earthquake, the static and dynamic elastic-plastic three-dimensional finite element models of the structure are established by using the finite element software PERFORM-3D. In this project, PERFORM-3D software is used for static elastoplastic Pushover and dynamic elastoplastic time history analysis of the structure.
3.2. Establishment of finite element model

The finite element model of shock absorption analysis is established. The beam and column components adopt the spatial beam column element. The model after completion is shown in the figure below.

![Figure 1. 3D view of finite element model](image1)

![Figure 2. Elevation view of finite element model](image2)

![Figure 3. Plane view of finite element model](image3)

Make a preliminary judgment on the accuracy of the model. The dynamic characteristics of the structure are calculated, and the first 5 order results are compared with the calculation results of the SATWE model. Therefore, the dynamic characteristics of the two systems are consistent.

| order | YJK | PERFORM-3D | Error  |
|-------|-----|------------|--------|
| 1     | 3.12| 3.00       | -3.92% |
| 2     | 2.88| 2.79       | -2.88% |
| 3     | 2.51| 2.50       | -0.47% |
| 4     | 1.31| 1.25       | -4.47% |
| 5     | 0.97| 0.94       | -3.10% |
| 6     | 0.89| 0.85       | -4.37% |
The algorithm of error rate in the table is as follows:

\[
\text{Error rate} = \left( \frac{|\text{SATWE} - \text{PERFORM}|}{\text{SATWE}} \right) \times 100\%
\]  

(1)

4. Evaluation of input earthquake

The structural response under the input of large earthquakes is given below, and the analysis of the structural response under the input of moderate earthquakes will not be repeated.

4.1. Response of structure under large earthquake input

4.1.1. Hysteretic curve of brace under X-direction seismic wave input

![Figure 4. Hysteresis curve of support under NGA803 input](image)

![Figure 5. Hysteretic curve of brace under nga1158 input](image)
4.1.2. **Hysteresis curve of support under Y direction seismic wave input**

*Figure 6. Hysteretic curve of 7451 input lower support*

*Figure 7. Hysteretic curve of brace under nga803 input*
4.2. Overall response evaluation of structure under large earthquake

The following table shows the maximum interlayer displacement angle of the shock-absorbing structure when each group of seismic waves is input. When the seismic wave is input in the X direction, the maximum interstory displacement angles of the damping structure are 1/64, 1/72 and 1/68 respectively (nga803, nga1158 and l7451), and the envelope value is 1/64, which is less than the limit value of 1/50. Seismic waves are mainly input in the y direction, and the maximum inter-story displacement angles of the damping structure are 1/84, 1/98 and 1/72 (NGA803, NGA1158 and L7451), respectively, and the envelope value is 1/72, which is less than 1/50 limit.
### Table 4. Maximum interlayer displacement angle in X-direction elastoplastic structure

| Floor number | XNGA803 | XNGA1158 | XL7451 | Envelope |
|--------------|---------|----------|--------|----------|
| 10           | 1/204   | 1/150    | 1/173  | 1/150    |
| 9            | 1/189   | 1/108    | 1/137  | 1/108    |
| 8            | 1/171   | 1/146    | 1/157  | 1/146    |
| 7            | 1/84    | 1/75     | 1/79   | 1/75     |
| 6            | 1/64    | 1/72     | 1/68   | 1/64     |
| 5            | 1/74    | 1/79     | 1/77   | 1/74     |
| 4            | 1/77    | 1/99     | 1/86   | 1/77     |
| 3            | 1/108   | 1/114    | 1/111  | 1/108    |
| 2            | 1/179   | 1/138    | 1/158  | 1/138    |
| 1            | 1/162   | 1/119    | 1/126  | 1/119    |

### Table 5. Maximum interlayer displacement angle in Y-direction elasto-plastic structure

| Floor number | YNGA803 | YNGA1158 | YL7451 | Envelope |
|--------------|---------|----------|--------|----------|
| 10           | 1/269   | 1/179    | 1/241  | 1/179    |
| 9            | 1/184   | 1/132    | 1/193  | 1/132    |
| 8            | 1/162   | 1/125    | 1/184  | 1/125    |
| 7            | 1/175   | 1/145    | 1/160  | 1/145    |
| 6            | 1/206   | 1/152    | 1/145  | 1/145    |
| 5            | 1/103   | 1/111    | 1/184  | 1/184    |
| 4            | 1/107   | 1/103    | 1/72   | 1/72     |
| 3            | 1/84    | 1/98     | 1/74   | 1/74     |
| 2            | 1/101   | 1/99     | 1/106  | 1/99     |
| 1            | 1/97    | 1/83     | 1/80   | 1/80     |

### 4.3. Overall deformation and damage of the structure

In the rare earthquake, the overall damage degree of the structure is low, and some frame beams exceed the first performance level. The frame columns as key components do not exceed the first performance level. A few frame beams yield, exceeding the third performance level. The structure can meet the requirements of the non overturning performance of large earthquakes in rare earthquake.
Figure 10. The first performance level  Figure 11. Second performance level

Figure 12. Third performance level
5. Checking calculation of beam and column connected with buckling restraint support

5.1. Load effect and combination

When checking the bearing capacity of a member, the partial coefficient of its load or action shall be as follows, and the most unfavorable combination of each component should be used for cross-section design.

Table 6. Design load sub-factor

| combination                                    | Dead load | Mobile load | Earthquake (level) | Temperature |
|-----------------------------------------------|-----------|-------------|--------------------|-------------|
|                                               | Unfavorable | Favorable | Disadvantageous | Favorable | Wind |                      |             |
| 1 DEAD LOAD + LIVE LOAD                       | 1.35      | 0.7(1) ×1.4 | 0.0               | -          | -    |                      |             |
| 2 DEAD LOAD + LIVE LOAD                       | 1.20      | 1.0        | 1.4               | 0.0        | -    |                      |             |
| 3 DEAD LOAD + LIVE LOAD + WIND                | 1.20      | 0.7(1) ×1.4 | 0.0               | 1.0 ×1.4   | -    |                      |             |
| 4 DEAD LOAD + LIVE LOAD + WIND + horizontal earthquake | 1.20      | 0.5 ×1.4   | 0.5               | -          | 1.3  | 0.7                  |             |
| 5 DEAD LOAD + LIVE LOAD + horizontal earthquake | 1.20      | 0.5 ×1.4   | 0.5               | -          | 1.3  | 0.7                  |             |
| 6 DEAD LOAD + WIND + horizontal earthquake     | 1.20      | 0.5 ×1.4   | 0.5               | 0.2 ×1.4   | 1.3  | 0.7                  |             |
| 7 GRAVITY LOAD + WIND + TEMPERATURE            | 1.20      | 0.7 ×1.4   | 0.0               | 0.6 ×1.4   | 0.7  |                      |             |
| 8 GRAVITY LOAD + WIND + TEMPERATURE            | 1.20      | 0.7 ×1.4   | 0.0               | 0.6 ×1.4   | 0.7  |                      |             |
| 9 GRAVITY LOAD + WIND + TEMPERATURE            | 1.20      | 0.7 ×1.4   | 0.0               | 1.4        | 0.7  |                      |             |

5.2. Checking calculation of bearing capacity of concrete filled steel tubular frame column connected with BRB

In this paper, the ultimate flexural bearing capacity and shear elasticity of frame columns and beams connected with BRB under strong earthquake are checked.

For a reinforced concrete column with a certain section size and material properties, the limit internal forces Nu, Mx, and My can be determined through experiments with different bidirectional eccentricities, and the corresponding rugby-ball-shaped envelope surface can be drawn. As shown below. The intersection of this envelope surface and the 3 coordinates are the axial compression bearing capacity N0 and the unidirectional limit bending moments Mx0 and My0 (N=0) in the X and Y directions, respectively. It and the intersection of the two vertical coordinates N0-Mx0 and N0-My0 represent the limit axial force-bending moment envelopes of unidirectional eccentricity in the X and Y directions, respectively, on which (Mxb, Nb) and (Myb, Nb) ) is the limit eccentric state, and the intersection line Mx0 -My0 between it and the horizontal coordinate plane is the envelope of bidirectional bending (N=0).
The checking process is as follows. The internal force and reinforcement of the frame columns adjacent to BRB are given in the table below. The checking results show that the concrete-filled steel tubular columns adjacent to BRB meet the shear elastic requirements of large earthquake.
Table 7. Internal force and shear capacity of concrete-filled steel tubular frame columns under rare earthquake

| Story | Column | name | Column width 1 (mm) | Column width 2 (mm) | M2 max | M3 max | V2 max | V3 max | X-direction shear utilization | Utilization ratio of shear force in Y direction |
|-------|--------|------|---------------------|--------------------|--------|--------|--------|--------|-----------------------------|---------------------------------------------|
| STORY5 | C5000068 | CSD2 | 800                | 700                | 588    | 592    | 277    | 330    | 5.2%                        | 7.2%                                        |
| STORY5 | C5000069 | CSD2 | 800                | 700                | 613    | 568    | 324    | 239    | 6.1%                        | 5.2%                                        |
| STORY5 | C5000070 | CSD2 | 800                | 700                | 632    | 581    | 332    | 345    | 6.2%                        | 7.5%                                        |
| STORY5 | C5000071 | CSD2 | 800                | 700                | 572    | 584    | 332    | 318    | 6.2%                        | 6.9%                                        |
| STORY5 | C5000074 | CSD2 | 800                | 700                | 572    | 599    | 317    | 261    | 5.9%                        | 5.7%                                        |
| STORY5 | C5000075 | CSD2 | 800                | 700                | 598    | 597    | 278    | 282    | 5.2%                        | 6.1%                                        |
| STORY5 | C5000077 | CSD2 | 800                | 700                | 577    | 584    | 337    | 282    | 6.3%                        | 6.1%                                        |
| STORY5 | C5000078 | CSD2 | 800                | 700                | 580    | 611    | 325    | 312    | 6.1%                        | 6.8%                                        |
| STORY4 | C4000079 | CSD2 | 800                | 700                | 553    | 516    | 201    | 331    | 3.8%                        | 7.2%                                        |
| STORY4 | C4000081 | CSD2 | 800                | 700                | 529    | 510    | 334    | 317    | 6.3%                        | 6.9%                                        |
| STORY4 | C4000086 | CSD2 | 800                | 700                | 536    | 540    | 303    | 211    | 5.7%                        | 4.6%                                        |
| STORY4 | C4000088 | CSD2 | 800                | 700                | 583    | 521    | 200    | 226    | 3.8%                        | 4.9%                                        |
| STORY4 | C4000091 | CSD2 | 800                | 700                | 545    | 527    | 345    | 238    | 6.5%                        | 5.2%                                        |
| STORY4 | C4000093 | CSD2 | 800                | 700                | 561    | 542    | 314    | 313    | 5.9%                        | 6.8%                                        |
| STORY3 | C3000079 | CSD2 | 800                | 700                | 481    | 471    | 208    | 300    | 3.9%                        | 6.5%                                        |
| STORY3 | C3000081 | CSD2 | 800                | 700                | 610    | 469    | 295    | 268    | 5.5%                        | 5.8%                                        |
| STORY3 | C3000086 | CSD2 | 800                | 700                | 659    | 463    | 298    | 375    | 5.6%                        | 8.1%                                        |
| STORY3 | C3000087 | CSD2 | 800                | 700                | 475    | 510    | 334    | 293    | 6.3%                        | 6.4%                                        |
| STORY3 | C3000088 | CSD2 | 800                | 700                | 495    | 461    | 305    | 210    | 5.7%                        | 4.6%                                        |
| STORY3 | C3000089 | CSD2 | 800                | 700                | 516    | 480    | 207    | 225    | 3.9%                        | 4.9%                                        |
| STORY3 | C3000091 | CSD2 | 800                | 700                | 482    | 526    | 344    | 233    | 6.5%                        | 5.1%                                        |
| STORY3 | C3000093 | CSD2 | 800                | 700                | 521    | 465    | 309    | 303    | 5.8%                        | 6.6%                                        |
| STORY2 | C2000069 | CSD2 | 800                | 700                | 456    | 467    | 210    | 276    | 3.9%                        | 6.0%                                        |
| STORY2 | C2000071 | CSD2 | 800                | 700                | 606    | 497    | 293    | 278    | 5.5%                        | 6.0%                                        |
| STORY2 | C2000076 | CSD2 | 800                | 700                | 655    | 476    | 280    | 356    | 5.3%                        | 7.7%                                        |
| STORY2 | C2000077 | CSD2 | 800                | 700                | 455    | 560    | 355    | 273    | 6.7%                        | 5.9%                                        |
| STORY2 | C2000078 | CSD2 | 800                | 700                | 485    | 514    | 323    | 222    | 6.1%                        | 4.8%                                        |
| STORY2 | C2000079 | CSD2 | 800                | 700                | 506    | 481    | 218    | 206    | 4.1%                        | 4.5%                                        |
| STORY2 | C2000081 | CSD2 | 800                | 700                | 460    | 562    | 355    | 217    | 6.7%                        | 4.7%                                        |
| STORY2 | C2000083 | CSD2 | 800                | 700                | 516    | 489    | 309    | 291    | 5.8%                        | 6.3%                                        |
| STORY1 | C1000071 | CSD1 | 800                | 700                | 733    | 491    | 254    | 434    | 4.8%                        | 9.4%                                        |
| STORY1 | C1000073 | CSD1 | 800                | 700                | 476    | 537    | 303    | 257    | 5.7%                        | 5.6%                                        |
| STORY1 | C1000078 | CSD1 | 800                | 700                | 536    | 500    | 218    | 253    | 4.1%                        | 5.5%                                        |
| STORY1 | C1000079 | CSD1 | 800                | 700                | 672    | 509    | 247    | 348    | 4.0%                        | 7.6%                                        |
| STORY1 | C1000080 | CSD1 | 800                | 700                | 473    | 610    | 240    | 251    | 4.5%                        | 5.4%                                        |
| STORY1 | C1000081 | CSD1 | 800                | 700                | 496    | 631    | 251    | 201    | 4.7%                        | 4.4%                                        |
| STORY1 | C1000083 | CSD1 | 800                | 700                | 489    | 554    | 312    | 205    | 5.9%                        | 4.4%                                        |
| STORY1 | C1000085 | CSD1 | 800                | 700                | 558    | 495    | 225    | 313    | 4.2%                        | 6.8%                                        |

Calculation of flexural capacity of concrete-filled steel tubular columns
The following figure shows the relationship between the PM bearing capacity envelope and the PM internal force of the concrete-filled steel tube frame column adjacent to the BRB in the X-direction.
and Y-direction input of ground motions. It can be seen that the PM points of all the columns adjacent to the BRB are equal within the envelope. It shows that the compression-bending relationship of these columns meets the requirements of non-yielding in large earthquakes.

**Figure 17.** Envelope diagram of column bearing capacity
5.3. Checking calculation of bearing capacity of steel frame beam connected with BRB under large earthquake

Table 8. Internal force and reinforcement of frame beam connected with BRB under strong earthquake

| Story | Name                        | Steel grade | Sh MAX | Bending moment Max | Height (m) | Width of flange (m) | Flange thickness (mm) | Web thickness (mm) | Design value of bending strength (N/mm²) | Design value of shear strength (N/mm²) | Shear utilization | Normal section compression utilization rate |
|-------|-----------------------------|-------------|--------|--------------------|------------|---------------------|----------------------|-------------------|---------------------------------------|----------------------------------------|-----------------|------------------------------------------|
| STO   | RY5 B800X350X20X20X350X20GXQ235 | Q2 35       | 29     | 8                  | 489        | 800                 | 35                   | 20                | 20                                   | 215                     | 125             | 4.56%                                    | 5.69%                                |
| STO   | RY5 B800X350X20X20X350X20GXQ235 | Q2 35       | 34     | 9                  | 503        | 800                 | 35                   | 20                | 20                                   | 215                     | 125             | 5.39%                                    | 5.98%                                |
| STO   | RY5 B800X350X20X20X350X20GXQ235 | Q2 35       | 33     | 8                  | 500        | 800                 | 35                   | 20                | 20                                   | 215                     | 125             | 5.14%                                    | 6.07%                                |
| STO   | RY4 B800X350X20X20X350X20GXQ235 | Q2 35       | 29     | 7                  | 484        | 800                 | 35                   | 20                | 20                                   | 215                     | 125             | 4.59%                                    | 5.85%                                |
| STO   | RY4 B800X350X20X20X350X20GXQ235 | Q2 35       | 32     | 0                  | 471        | 800                 | 35                   | 20                | 20                                   | 215                     | 125             | 4.80%                                    | 5.52%                                |
| STO   | RY4 B800X350X20X20X350X20GXQ235 | Q2 35       | 30     | 5                  | 460        | 800                 | 35                   | 20                | 20                                   | 215                     | 125             | 4.65%                                    | 5.52%                                |
| STO   | RY3 B800X350X20X20X350X20GXQ235 | Q2 35       | 29     | 5                  | 479        | 800                 | 35                   | 20                | 20                                   | 215                     | 125             | 4.35%                                    | 5.64%                                |
| STO   | RY3 B800X350X20X20X350X20GXQ235 | Q2 35       | 30     | 9                  | 458        | 800                 | 35                   | 20                | 20                                   | 215                     | 125             | 4.54%                                    | 5.61%                                |
| STO   | RY3 B800X350X20X20X350X20GXQ235 | Q2 35       | 28     | 6                  | 431        | 800                 | 35                   | 20                | 20                                   | 215                     | 125             | 4.32%                                    | 4.86%                                |
| STO   | RY2 B800X350X20X20X350X20GXQ235 | Q2 35       | 29     | 4                  | 477        | 800                 | 35                   | 20                | 20                                   | 215                     | 125             | 4.38%                                    | 5.71%                                |
| STO   | RY2 B800X350X20X20X350X20GXQ235 | Q2 35       | 29     | 9                  | 441        | 800                 | 35                   | 20                | 20                                   | 215                     | 125             | 4.53%                                    | 5.44%                                |
| STO   | RY2 B800X350X20X20X350X20GXQ235 | Q2 35       | 28     | 2                  | 434        | 800                 | 35                   | 20                | 20                                   | 215                     | 125             | 4.13%                                    | 5.28%                                |
| STO   | RY1 B850X400X24X20X400X24GXQ235 | Q2 35       | 29     | 4                  | 500        | 850                 | 40                   | 24                | 20                                   | 215                     | 125             | 4.07%                                    | 4.64%                                |
| STO   | RY1 B850X400X24X20X400X24GXQ235 | Q2 35       | 32     | 2                  | 479        | 850                 | 40                   | 24                | 20                                   | 215                     | 125             | 4.49%                                    | 4.43%                                |
| STO   | RY1 B850X400X24X20X400X24GXQ235 | Q2 35       | 32     | 7                  | 503        | 850                 | 40                   | 24                | 20                                   | 215                     | 125             | 4.63%                                    | 4.57%                                |

The results show that the steel frame beams and concrete-filled steel tubular frame columns connected with BRB meet the requirements of bending capacity and shear elasticity.

6. Evaluation and conclusion of structural seismic performance

Through the seismic design and dynamic elastoplastic analysis of the system, the following conclusions can be drawn:

(1) Buckling restrained braces remain elastic under frequent earthquakes
The yield force of BRB is 1500kN, which is about twice the internal force of the BRB response spectrum. This ensures that BRB remains resilient under frequent earthquakes.

(2) Under rare earthquake, the type and quantity structure of the damping knot support after the damper is configured meet the seismic performance design goal.

When the seismic wave is input in the X direction, the envelope value of the displacement angle is 1/64, which is less than the limit value of 1/50. The seismic wave is input in the Y direction as the main direction, and the displacement angle envelope value of the damping structure is 1/72, which is less than the limit of 1/50. Under rare earthquake, BRB takes the lead in energy consumption, followed by frame beams, and the damage of frame columns is small, which meets the requirements of structural seismic conceptual design.

In general, the BRB layout scheme can protect the main structure well under rare earthquake intensity input, and can achieve the goal of ensuring life safety.

(3) Arrangement principle of buckling restraint supports

By summarizing the seismic analysis process of the structure, the layout principle of buckling restrained braces can be summarized. Buckling braces should be arranged at positions that can exert their energy dissipation function to the maximum extent, without affecting the building function and layout, and meet the overall stress requirements of the structure. The buckling restrained brace can be arranged according to the following principles: ① The position where the internal force of the brace is larger under the earthquake. ② The story with large displacement between the lower floors under earthquake action. ③ It should be set separately along the two main axes of the structure. ④ Single diagonal bracing, herringbone or V-shaped bracing can be used, and eccentric bracing can also be used. When eccentric bracing is used, the bracing should yield before the frame beam in the design.

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