Extraction Method of Design Element Forces and Moments from 3D-FEM Seismic Response Analysis

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Abstract

The seismic response analysis employing 3D-FEM model is recently applied to seismic design for the nuclear power buildings. The advantage of this approach is that element forces and moments obtained from the seismic response analysis results can be directly used for the section calculation of walls, slabs, beams and columns which are modeled by shell elements and beam elements. However, the element forces and moments are time history output along with the seismic input motion, and therefore, the huge amount of output data causes the difficulty to perform the section calculation in time domain in terms of practical calculation time. One of the simple and practical approaches is to use the maximum values, however, this approach may result in over conservative design due to the assumption of coincidental occurrence of the maximum element forces and moments.

This paper proposes two data extraction methods from time history element forces and moments not to be over conservative design and not to be non-conservative design. One of the proposed methods is applying the convex hull algorithm by which the smallest number of data set enveloping the relationship diagrams among all components of the element forces and moments can be extracted. In case of the shell elements, four-dimensional convex hull data is obtained from four components of element forces and moments such as axial force, out-of-plane bending moment, in-plane shear and torsional moment. The number of extracted data is about 1/20 of total number of time history data in this study. The notable point of this approach is that the results of section calculation are identical to those calculated from whole time history output data and no conservativeness is included in the data extraction process.

The other proposed method is approximating two-dimensional relationship diagrams between axial force and out-of-plane bending moment (P-M) by the enveloping hexagonal shape to extract data at the six vertexes. The directional characteristic, e.g., the maximum values for two components of element forces and moments are occurred almost at the same time, observed in the P-M diagram is considered. For the other components such as in-plane shear and torsional moment, the maximum values are used since the directional characteristic in these components is relatively small. The notable point of this approach is to reduce the number of extracted data compared with the above method and can save the computation time of section calculation. Although some conservativeness is included in this data extraction process, this method reduces the overconservativeness which may be included in the approach using the maximum values for all components.

Keywords: Seismic Response Analysis, 3D-FEM, data extraction method, convex hull algorithm, hexagonal shape

1. Introduction

The seismic response analysis employing 3D-FEM model is recently applied to seismic design for the nuclear power buildings. The advantage of this approach is that element forces and moments obtained from the seismic response analysis results can be directly used for the section calculation of walls, slabs, beams and columns which are modeled by shell elements and beam elements. However, the element forces and moments are time history output along with the seismic input motion, and therefore, the huge amount of output data causes the difficulty to perform the section calculation in time domain in terms of practical calculation time. One of the simple and practical approaches is to use the maximum values, however, this approach may result in over conservative design due to the assumption of coincidental occurrence of the maximum element forces and moments.

This paper proposes two data extraction methods from time history element forces and moments not to be over conservative design and not to be non-conservative design. One of the proposed methods is applying the convex hull algorithm by which the smallest number of data set enveloping the relationship diagrams among all components of the element forces and moments can be extracted. The other proposed method is approximating two-dimensional relationship diagrams between axial force and out-of-plane bending moment by the enveloping hexagonal shape to extract data at the six vertexes.

The trial section calculation using the proposed methods for a simple pilot model are conducted in this paper. The comparison with the result using whole time history section calculation demonstrates the applicability of the proposed methods. The comparison with the results using maximum values clarifies the mitigation of conservative design by the proposed methods.

2. Design Flow

The design flow using 3D-FEM model is shown in Fig. 1. The same 3D-FEM model of the structure may be used for both seismic response analysis and static stress analysis. The soil is usually considered with seismic input motion to perform soil-structure interaction (SSI) analysis in the seismic analysis. The static loads such as dead load, live load and wind load, etc. are considered in the static stress analysis. The element forces and moments obtained from the seismic response analysis and the static stress analysis are combined according to design criteria. The section calculation is conducted for all combined element forces and moments to ensure the size of structure and the amount of rebar are sufficient.

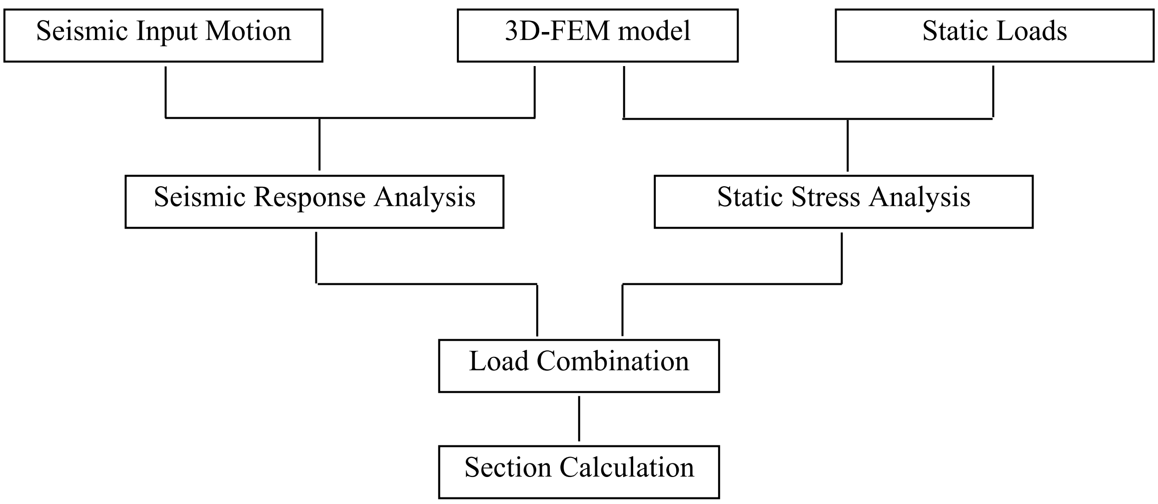

Fig. 1 – Design Flow

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The element forces and moments directly obtained from the seismic response analysis are time history output along with the seismic input motion. The section calculation for all time history is time consuming and wasteful since number of critical sets of element forces and moments for section design is limited. The maximum values are usually used to ensure the worst stress condition. However, this approach may result in over conservative design due to the assumption of coincidental occurrence of the maximum element forces and moments. This paper focuses on the data extraction methods from time history element forces and moments to resolve the above problem.

3. Data Extraction Method

The data extraction methods from time history element forces and moments are shown in the following subsections for the reinforced concrete (RC) structure design. There are three methods and two of them except for maximum value extraction method are proposed in this paper.

3.1 Maximum Value Extraction

One of the simple and practical approaches is to use the maximum values. The absolute maximum values are usually extracted from time history output. Both plus and minus values are used with consideration for positive and negative alternating characteristics of seismic response. The example of the extracted data on axial force and out-of-plane bending moment (P-M) diagram is shown in Fig. 2.

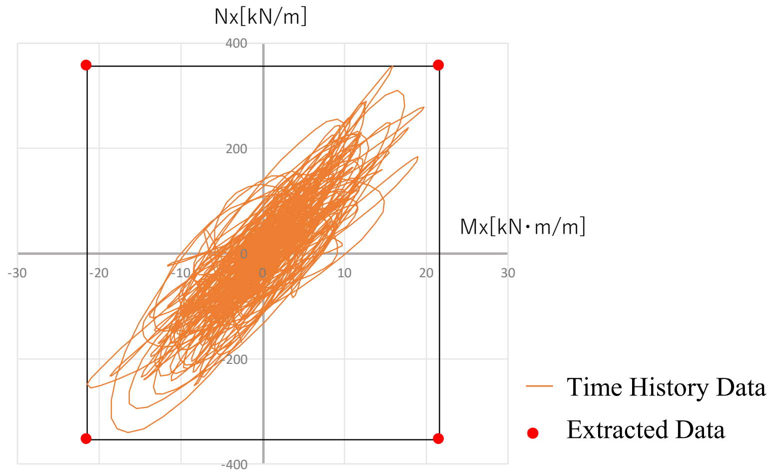

Fig. 2 – Maximum Value Extraction

In case of shell element, four components of element forces and moments such as axial force, out-of-plane bending moment, in-plane shear and torsional moment are used for section design in one direction according to design code of RC structure such as ACI349 [2]. The four components shown by variables are (Nx, Mx, Nxy, Mxy) for x-direction and (Ny, My, Nxy, Mxy) for y direction, where Nx and Ny are axial forces in x-direction and y-direction, Mx and My are out-of-plane bending moments around y-axis and x-axis, Nxy is in-plane shear, and Mxy is torsional moment. The combination number of seismic forces and moment is 2^4=16 in each direction. Therefore, the section calculation time can be minimized. However, there is a possibility to result in over conservative design since the maximum or minimum forces and moments may not occur at the same time as shown in Fig. 2.

3.2 Convex Hull Algorithm Extraction

One of the proposed methods in this paper is applying the convex hull algorithm. The representative literature of the convex hull algorithm is shown in Reference [1]. The smallest number of data set convexly enveloping the relationship diagrams among all components of the element forces and moments can be extracted. The examples of the extracted data on P-M diagram are shown in Fig. 3 (a) for two-dimensional extraction and Fig. 3 (b) for four-dimensional extraction. The time history output is enveloped by a convex

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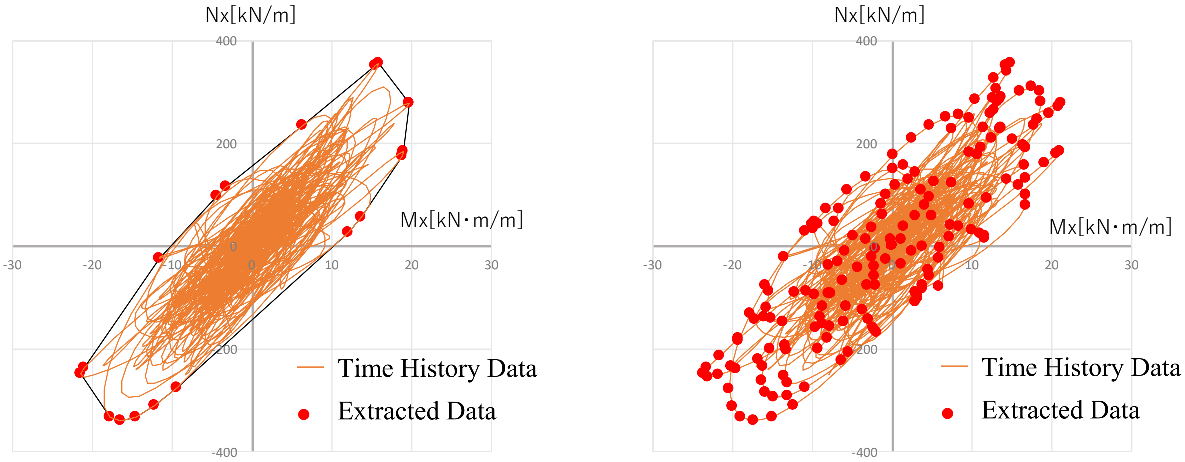
polygon in two-dimensional relationship as shown in Fig. 3 (a). In case of three-dimensional relationship, the time history output is enveloped by a convex polyhedron. And in case of four-dimensional or more relationship, convex hull data is obtained by applying the same algorithm.



(a) Two-dimensional Extraction (Nx, Mx) (b) Four-dimensional Extraction (Nx, Mx, Nxy, Mxy)

Fig. 3 – Convex Hull Algorithm Extraction

In case of shell element, four-dimensional convex hull data is obtained from four components of element forces and moments described in above 3.1. The number of extracted data is reduced to about 1/20 of total number of time history data in each direction for the pilot model in Section 4. About 200 sets of data are extracted out of 4000 sets of time history data. Therefore, the section calculation time can be shortened by 1/20 compared to that by whole time history output data. However, the section calculation time is about 12.5 times longer than that by maximum value extraction method.

The notable point of this approach is that the results of section calculation are identical to those calculated from whole time history output data and no conservativeness is included in the data extraction process as shown in Section 4.

3.3 Hexagonal Shape Extraction

The other method proposed in this paper is approximating P-M diagrams by enveloping hexagonal shape to extract data at the six vertexes. The example of the extracted data is shown in Fig. 4.

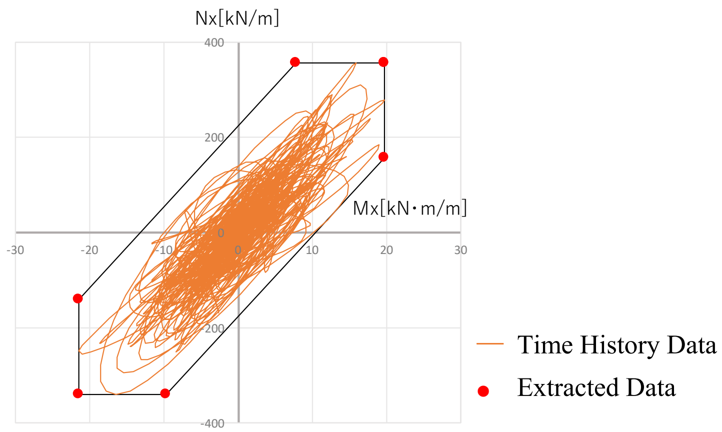


Fig. 4 – Hexagonal Shape Extraction

The directional characteristic, e.g., the maximum values for two components of element forces and moments are occurred almost at the same time, is observed in the P-M diagram as shown in Fig. 4. For the

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other components such as in-plane shear and torsional moment, the maximum value extraction method is applied since the directional characteristic in these components is relatively small.

In case of shell element, the combination number of seismic forces and moments is 6 x 2^2=24 in each direction. Therefore, the section calculation time can be shortened by about 1/8 compared to the convex hull algorithm extraction method. Although some conservativeness is included in the data extraction process, this method reduces the overconservativeness which tends to be included in the approach by maximum value extraction method as shown in Section 4.

4. Section Calculation

The section calculation for element forces and moments extracted by the above three data extraction methods are conducted using a simple pilot model featuring nuclear power building. For comparison purpose, the section calculation using whole time history output data is also conducted.

4.1 Pilot Model

The simple pilot model to simulate the nuclear power buildings is shown in Fig. 5. It is the reinforced concrete (RC) structure with no embedment. There are two layers with 6 m each height and the total height is 12 m. There are two spans for both X and Y directions in the plane of 12 m x 14 m external dimensions. The thicknesses of the external walls are 0.8 m in shorter side and 0.6 m in longer side. The thickness of internal walls is 0.4 m. The thickness of floor slab and roof slab is 0.5 m.

Fixed-base condition is considered by assuming the structure is supported by stiff ground. The unit weight of RC structure of 25 kN/m^3 is defined. The representative dead load of 4.9 kN/m^2 is considered on the slabs. In order to fit the 1st natural frequency, about 8 Hz, of the representative nuclear power building, the additional mass is distributed at the top of the external walls.

For seismic response analysis, ACS SASSI is used, and for static stress analysis, NASTRAN is used. The damping factor of 4% is used for the seismic response analysis.

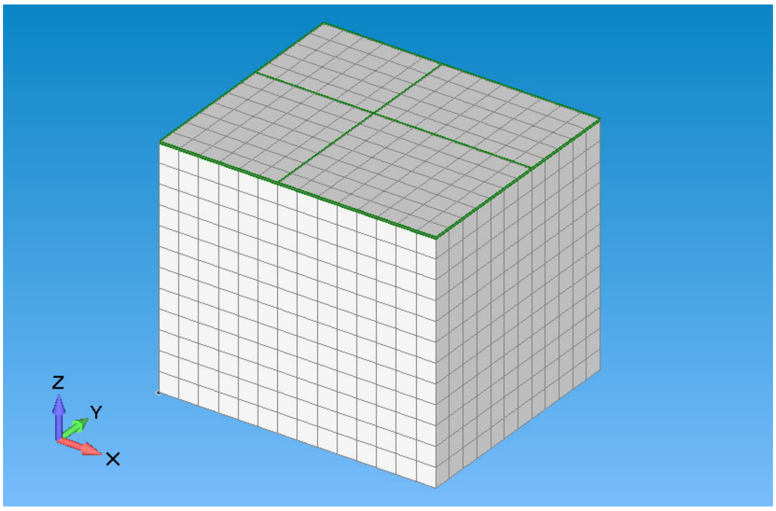

Fig. 5 – Pilot Model

4.2 Seismic Input Motion

The seismic input motions in two orthogonal horizonal directions and one vertical direction are created according to NRC Regulatory Guide 1.60 [3]. The maximum acceleration is 0.3g and time duration and time interval are 20 sec and 0.005 sec, respectively. The time histories of the seismic input motion for three direction are shown in Fig. 6. The responses due to three directional inputs are combined by algebraic sum in time domain. The three orthogonal components are considered statistically independent since the mean

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correlation of the set is no greater than 0.16 with no single correlation of any two records greater than 0.3 according to ASCE4-16 [4].

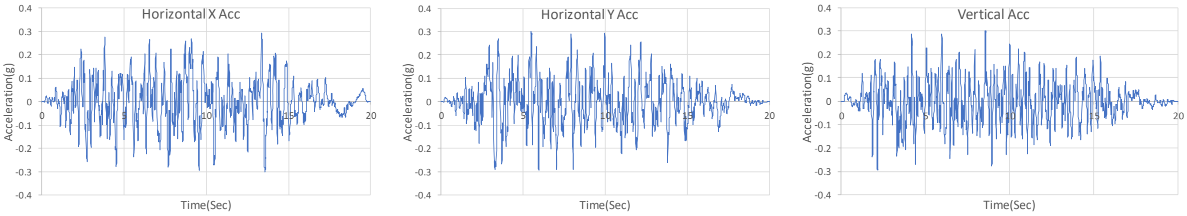

Fig. 6 – Seismic Input Motion

4.3 Section Calculation Method

Load combination between seismic load and dead load is considered for this study.

The section calculation method based on ACI349 [2] is applied for the walls and slabs. The concrete strength f_c' = 35 MPa and the yield strength of rebar f_y = 420 MPa are used as the representative material for nuclear power buildings. The section calculation was performed by using the automated design tool for FE modelled reinforced concrete shell elements, SSDP-WS [5].

The ratios of required rebar section area to concrete section area in each orthogonal rebar direction are calculated for both in-plane shear and P-M interaction. The iterative calculation is used to evaluate the required rebar. The torsional moment is added to the out-of-plane bending moment for both directions according to ACI 447R (2018) [6].

4.4 Section Calculation Result

The results of section calculation for the selected elements are shown in Table 1 for walls and Table 2 for slabs. The locations of the selected elements are shown in Fig. 7. The breakdown of the required rebar ratio for the representative elements of wall and slab are shown in Table 3.

As shown in all tables, it is confirmed that the results of Convex Hull are identical to those of Time History. Therefore, the Convex Hull approach includes no conservativeness in data extraction process, and it is an ideal alternative of Time History approach.

As expected, the required rebar ratios of Max. Value are maximum 1.82 times larger than those of Convex Hull as shown in Tables 1 and 2. As shown in Table 3, the required rebar due to in-plane shear of the Max. Value is 1.44 times larger and that due to P-M is 2.5 times larger for the wall element. Basically, the direction of seismic input motion impacted to in-plane shear is horizontally in parallel with wall face. On the other hand, the direction impacted to P-M is orthogonal to wall face. The similar behavior is also expected for the slab. Therefore, the maximum in-plane shear and the maximum P-M may not be occurred at the same time. This is main factor of the conservativeness by Max. Value approach.

The required rebar ratios of Hex. Shape are maximum 30% smaller than those of Max. Value as shown in Tables 1 and 2. The conservativeness by Max. Value in the required rebar due to P-M is effectively mitigated by Hex. Shape as shown in Table 3. It shows reasonable results since the Hex. Shape approach is applied to P-M relationship only. The Hex. Shape approach is also expected to be effective to mitigate the conservativeness for external wall below grade which receive dynamic earth pressure.

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Table 1 – Required Rebar Ratio for External Walls

Location	Element ID	Rebar in Vertical Direction			
		Time History	Max. Value	Convex Hull	Hex. Shape
1st Floor Bottom	11	0.475	0.834 (1.756)	0.475 (1.000)	0.794 (1.671)
1st Floor Middle	67	0.439	0.779 (1.774)	0.439 (1.000)	0.749 (1.706)
2nd Floor Bottom	179	0.364	0.663 (1.824)	0.364 (1.000)	0.593 (1.632)
2nd Floor Middle	235	0.348	0.508 (1.459)	0.348 (1.000)	0.358 (1.029)

Note: Ratio to "Time History" is shown in parenthesis.

Table 2 – Required Rebar Ratio for Slabs

Location	Element ID	Rebar in Y-direction			
		Time History	Max. Value	Convex Hull	Hex. Shape
Roof End	40011	0.381	0.503 (1.319)	0.381 (1.000)	0.473 (1.240)
Roof Center	40039	0.303	0.357 (1.179)	0.303 (1.000)	0.307 (1.014)
2nd Floor End	50011	0.139	0.180 (1.293)	0.139 (1.000)	0.180 (1.293)
2nd Floor Center	50039	0.106	0.139 (1.321)	0.106 (1.000)	0.119 (1.131)

Note: Ratio to "Time History" is shown in parenthesis.

Table 3 – Breakdown of Required Rebar Ratio

Component	Items	Wall (ID:11) Rebar in Vertical Direction				Slab (ID:50039) Rebar in Y-direction			
		Time History	Max. Value	Convex Hull	Hex.Shape	Time History	Max. Value	Convex Hull	Hex. Shape
Element Forces and Moments	In-Plane Shear Force	1013.0	1463.3 (1.445)	1013.0 (1.000)	1463.3 (1.445)	140.0	149.7 (1.069)	140.0 (1.000)	149.7 (1.069)
	Axial Force [kN/m]	-307.6	-1234.4 (4.013)	-307.6 (1.000)	-1093.0 (3.553)	-8.5	-91.4 (10.753)	-8.5 (1.000)	-60.6 (7.129)
	Moment [kN·m/m]	84.1	96.8 (1.152)	84.1 (1.000)	85.3 (1.015)	35.5	43.5 (1.226)	35.5 (1.000)	40.6 (1.146)
Required Rebar Ratio	Due to In-Plane Shear	0.335	0.484 (1.444)	0.335 (1.000)	0.484 (1.444)	0.056	0.059 (1.069)	0.056 (1.000)	0.059 (1.069)
	Due to P-M	0.140	0.350 (2.500)	0.140 (1.000)	0.310 (2.214)	0.050	0.080 (1.600)	0.050 (1.000)	0.060 (1.200)
	Total	0.475	0.834 (1.756)	0.475 (1.000)	0.794 (1.671)	0.106	0.139 (1.321)	0.106 (1.000)	0.119 (1.131)

Note: Ratio to "Time History" is shown in parenthesis.
Negative values in axial force indicate tension.

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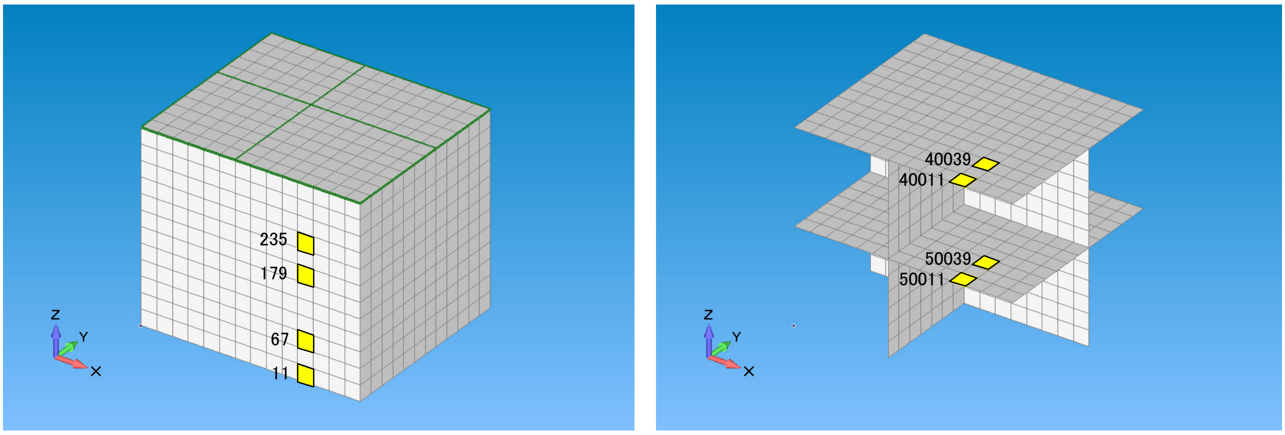

(a) Selected Elements on Walls (b) Selected Elements on Slabs

Fig. 7 – Selected Elements

5. Conclusions

This paper proposes two data extraction methods from time history element forces and moments not to be over conservative design and not to be non-conservative design.

One of the proposed methods is applying the convex hull algorithm. The section calculation results by this approach is confirmed to be identical to those by whole time history. The calculation time can be shortened by about 1/20 compared to that by whole time history. This approach includes no conservativeness in data extraction process, and it is an ideal alternative of time history approach.

The other proposed method is approximating two-dimensional relationship diagrams between axial force and out-of-plane bending moment by the enveloping hexagonal shape. The conservativeness by the maximum value extraction method is effectively mitigated by this approach.

6. References

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