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Application of Automated Design Tool for FE modelled Reinforced Concrete Line Elements to Seismic Design

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Abstract

The objective of the paper is to evaluate the development and application of an automated design tool in designing FE modelled reinforced concrete line elements, such as beams and columns, in accordance with ACI 349 [1].

The seismic and structural analysis for the nuclear facility structures has been performed recently by using the refined 3D-FEM model, to capture the detail force distribution of the complex nuclear structures. To process the large number of element force data produced by the 3D-FEM analysis with the vast number of load combinations, an automated design tool for FE modelled reinforced concrete line elements, SSDP-FM, has been developed [4]. The tool offers the flexibility to input various rebar arrangements and material properties, thus allowing the user to consider the effect of design changes. The tool develops the interaction curves for the element and obtains the required reinforcement percentage through iteration steps. In the case that rebar arrangement is provided, the utilization ratio (UR) is calculated for the given forces and moments. The process is performed under both uniaxial and biaxial bending.

This automated design tool allows even time history section design using the element forces and moments obtained from the seismic response analysis results directly. Although the section design in the time domain is time consuming calculation, it can reduce the conservativeness compared to the conventional method using the enveloped maximum values of forces and moments. To reduce the calculation time, two data extraction methods from time history element forces and moments are proposed [5]. One is the extraction method applying the convex hull algorithm. The other is approximating relationship diagrams between axial force and bending moment by six points with enveloping hexagonal shape. This paper provides sample calculation results using the developed automated tools to evaluated adequacy of the above two extraction methods by comparing their results with whole time history section calculation results.

Keywords: Automated design tool for RC line elements, 3D-FEM, data extraction method, convex hull algorithm, hexagonal shape

1. Introduction

The seismic and structural analysis for the nuclear facility structures has been performed recently by using the refined 3D-FEM model, to capture the detail force distribution of the complex nuclear structures. To process the large number of element force data produced by the 3D-FEM analysis with the vast number of load combinations, an automated design tool for FE modelled reinforced concrete line elements has been developed in accordance with ACI 349 [1].

This automated design tool, SSDP-FM [4], allows even time history section design using the element forces and moments obtained from the seismic response analysis results directly. Although the section design in the time domain is time consuming calculation, it can reduce the conservativeness compared to the conventional method using the enveloped maximum values of forces and moments [5]. To reduce the calculation time, two data extraction methods from time history element forces and moments have been proposed [6]. One is the extraction method applying the convex hull algorithm. The other is approximating relationship diagrams between axial force and bending moment by six points with enveloping hexagonal shape.

This paper explained the capabilities and limitations of the developed automated design tool for FE modelled reinforced concrete line elements, SSDP-FM. Then, the trial section calculation using the proposed extraction methods for a simple pilot model are performed by using this tool. 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 for FE Line Element

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 of the line elements is conducted for all combined element forces and moments to ensure the section size and the amount of rebar are sufficient.

The capabilities and limitations of the automated design tool, SSDP-FM, [4] are as follows.

1) Determine if the element is slender/non-slender in each axis and magnify the moment according to the slenderness check.
2) Develop both ultimate and design axial force–moment capacity curves for both uniaxial directions of the RC sections with either symmetric or asymmetric rebar arrangement.
3) Calculate uniaxial URs for inputted section, material and load information, or required area of reinforcements.
4) Evaluate UR or required area of reinforcement for biaxial bending based on Bresler reciprocal load method and Bresler load contour method according to the approach discussed in the Portland Cement Association (PCA) notes to ACI 318-08 [3].
5) The shear capacity is calculated with the simplified method or detailed method according to ACI318M-08 [2]
6) Evaluate the area of reinforcement required for shear friction at construction joint.
7) The torsion capacity is not considered.

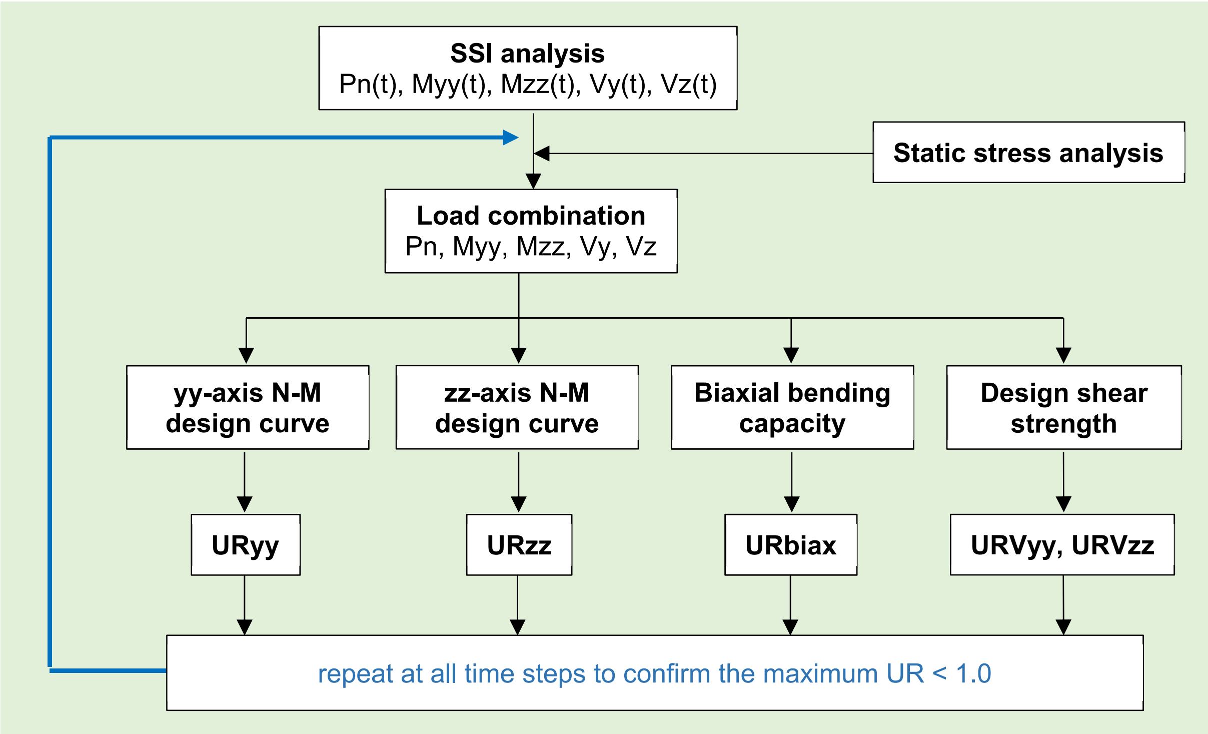


Fig. 1 – Design Flow for FE Line Element

3. Data Extraction Method

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 the critical 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. To resolve the above problem, the data extraction methods from time history element forces and moments are proposed in the accompanying paper, Yachi *et al*. (2020) [6].

The following subsections provide outlines of the three extraction methods.

3.1 Absolute Maximum Extraction

One of the simple and practical approaches is to use the maximum values. The absolute maximum values (Pn, Myy, Mzz, Vx, Vy) are usually extracted from time history output. For (Pn, Myy, Mzz), both plus and minus values are used with consideration for positive and negative alternating characteristics of seismic response. For (Vx, Vy), absolute values are used. The image of the extracted data on axial force and bending moment (P-M) diagram is shown in Fig. 2.

In this case, the combination number of seismic forces and moment is 2^3=8. 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 Hexagonal Shape Extraction

One of the proposed methods is approximating P-M diagrams by enveloping hexagonal shape to extract data at the six vertexes. The image of the extracted data is shown in Fig. 3. 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.

This extraction method is applied for both directions, yy-axis and zz-axis. Then they are combined to the bi-axis forces and moments. The combination number of seismic forces and moment become 12. Therefore, as this method considers the directional characteristic in the P-M diagram, it can reduce the conservativeness which may be included in the approach by absolute maximum extraction method.

3.2 Convex Hull Algorithm Extraction

Another proposed method is applying the convex hull algorithm. The representative literature of the convex hull algorithm is shown in Reference [7]. The smallest number of data set convexly enveloping the relationship diagrams among three components, Pn, Myy, Mzz, can be extracted. The image of the extracted data on P-M diagram is shown in Fig. 4, which shows that the time history output is enveloped by a convex polygon in two-dimensional relationship

In case of three-dimensional relationship, the time history output is enveloped by a convex polyhedron. The number of extracted data can be reduced largely from the total number of time history so that the section calculation time can be shortened rationally.

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.

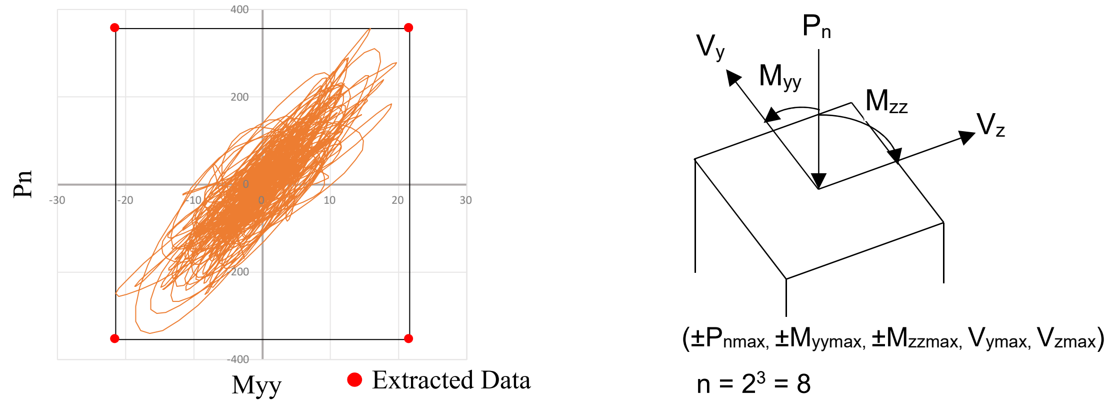


Fig. 2 Absolute Maximum Extraction

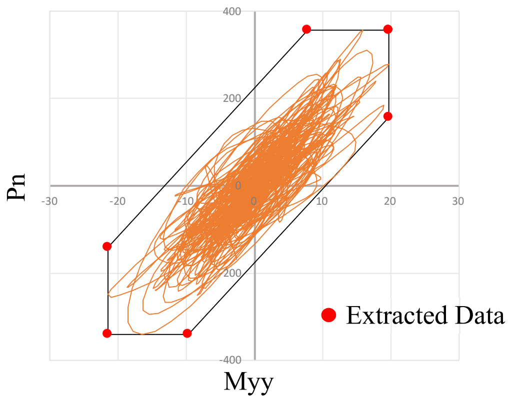


Fig. 3 Hexagonal Shape Extraction

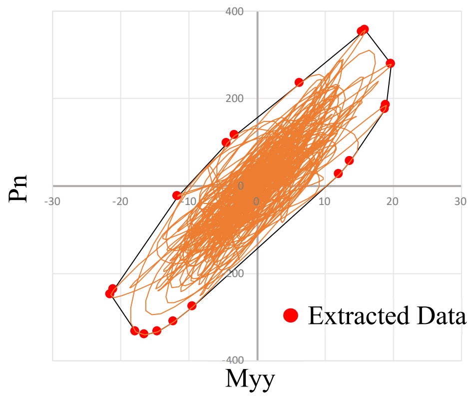


Fig. 4 Convex Hull Algorithm Extraction

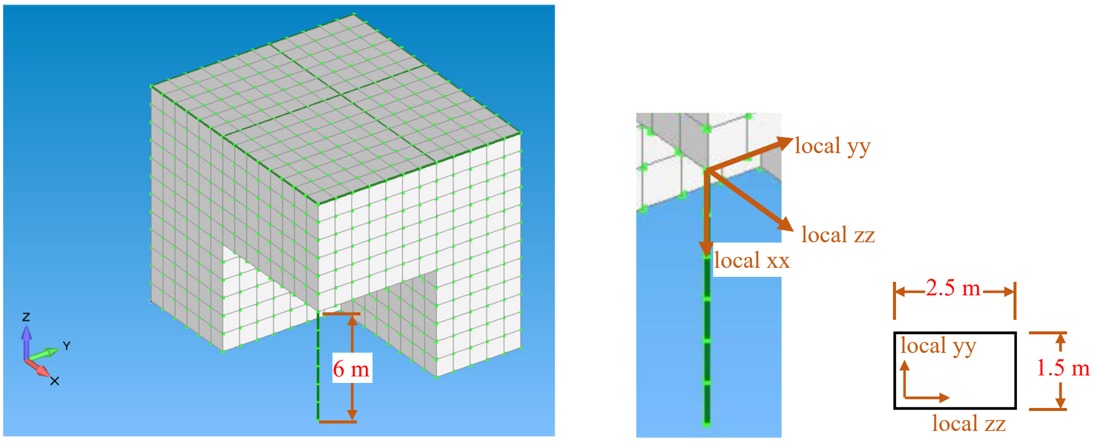
4. Section Calculation

The section calculation 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

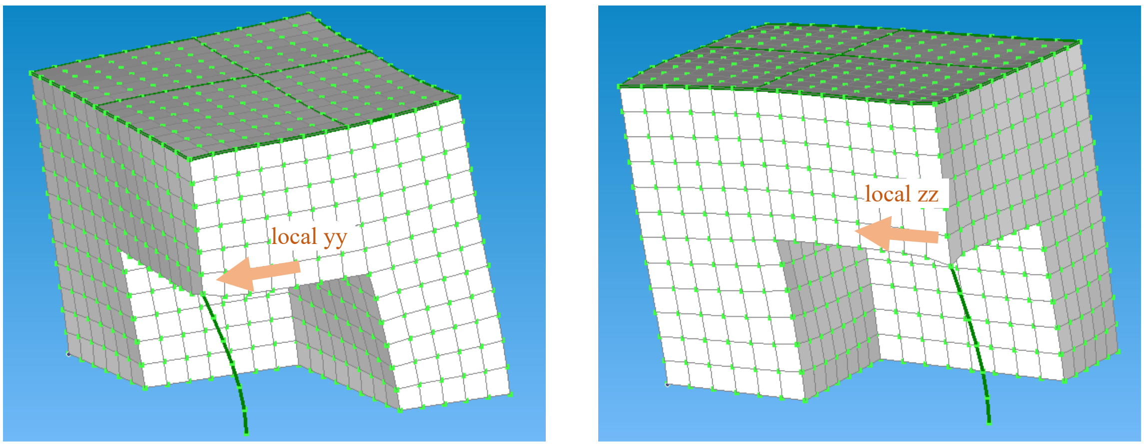
The simple pilot model to simulate the nuclear power buildings is shown in Fig. 5. It is the reinforced concrete (RC) structure with no embedment. There are two layers with 6 m each height and the total height is 12 m. There are two spans for both X and Y directions in the plane of 12 m x 14 m external 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. At the one corner of the bottom floor, column (2.5m x 1.5 m) are installed.

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 fundamental frequency, about 7 Hz, of the representative nuclear power building, the additional mass is distributed at the top of the external walls. The eigenvalue analysis results are shown in Fig. 6.



(a) overview of pilot model (b) local coordination of column

Fig. 5 Pilot Model



(a) 1st vibration mode (6.7 Hz) (b) 2nd vibration mode (7.3 Hz)

Fig. 6 Fundamental Frequency and Vibration Mode

4.2 Seismic Analysis

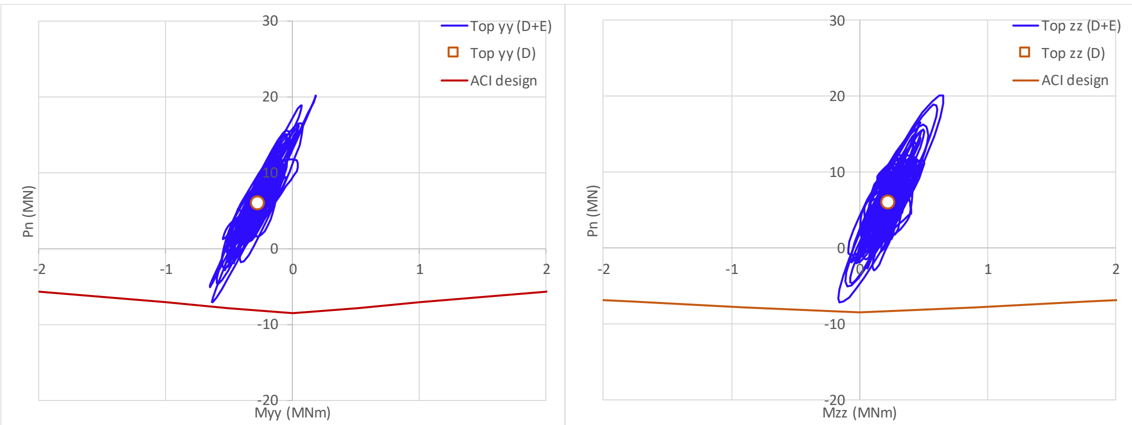
The seismic input motion in two orthogonal horizonal directions and one vertical direction are created according to Regulatory Guide 1.60 [8]. The maximum acceleration is 0.3g and time duration and time interval are 20 sec and 0.005 sec, respectively. The responses due to three directional inputs are combined by algebraic sum in time domain. The three orthogonal components are considered statistically independent since the mean 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 [9].

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.

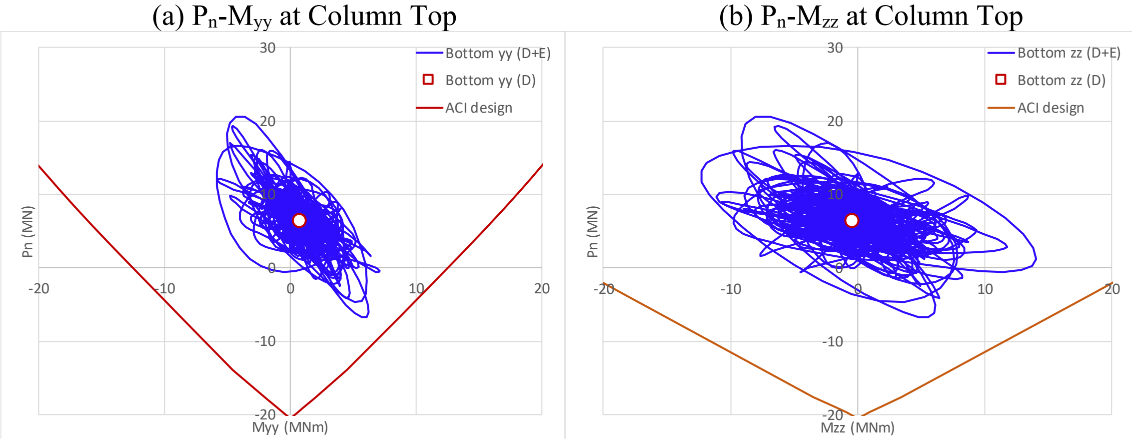
The obtained P-M time history at the column top and bottom are shown in Fig. 7. The legend (D) represents the axial force and moments by the dead load only and (D+E) represents those including the seismic responses. ACI design curve is calculated using the following properties and shown by the orange line.

Concrete strength	fc'	35 MPa
Rebar yielding strength	fy	420 MPa
Rebar ratio at column top		0.30 % (four sides)
Rebar ratio at column bottom		0.72 % (four sides)
Rebar distance from surface		200 mm (four sides)

It can be seen from Fig.7 that the moments at the column bottom are much larger than those at the column top because of the fixed base condition.



(a) P_n-M_{yy} at Column Top (b) P_n-M_{zz} at Column Top



(c) P_n-M_{yy} at Column Bottom (d) P_n-M_{zz} at Column Bottom

Fig. 7 P-M Time History at Column Top and Bottom

4.3 Section Calculation

Using the axial force and moments shown in Section 4.2, the section calculation is performed for the top and bottom of the column by the automated design tool, SSDP-FM [4]. Inputting the section properties shown in Section 4.2, SSDP-FM calculates two uniaxial utilization ratios, UR_{yy}, UR_{zz} and the biaxial utilization ratios, UR_{biax}.

UR for uniaxial bending is calculated by diving the applied loading P and M, by the intersection point of the design line and the ACI design interaction curve as shown in Fig. 8.

UR for biaxial bending is calculated using the Bresler Load Contour and the Bresler Reciprocal Load methods depending on the applied axial load, P_n. (Reference [3])

A. Bresler Reciprocal Load method when $P_n \geq 0.1\, fc'\, A_g$

$$\frac{1}{P_{ni}} = \frac{1}{P_{nx}} + \frac{1}{P_{ny}} - \frac{1}{P_o} \qquad UR_{Biax1} = \frac{P_n}{P_{ni}} < 1.0$$

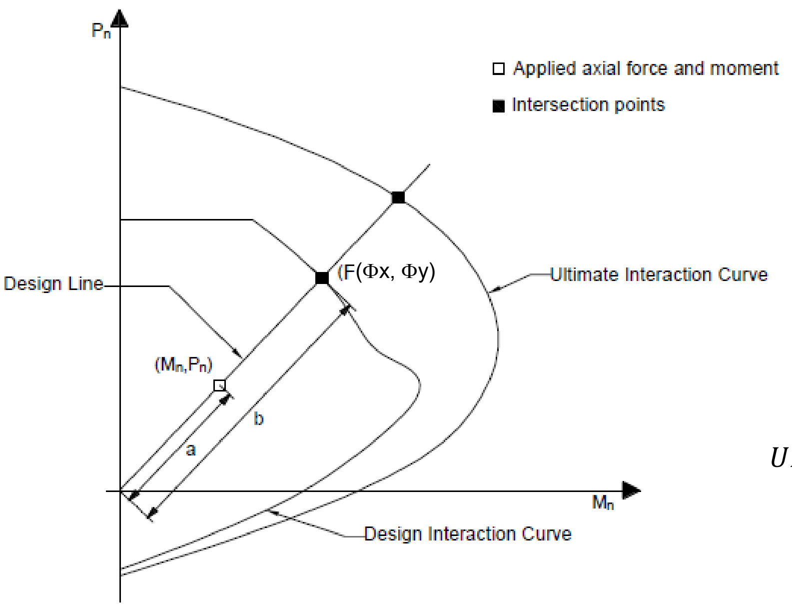
where:
P_{ni} = nominal axial load strength at given eccentricity along both axes
P_o = nominal axial load strength at zero eccentricity
P_{nx} = nominal axial load strength at given eccentricity along x-axis
P_{ny} = nominal axial load strength at given eccentricity along y-axis
P_n = axial load demand

B. Bresler Load Contour method when $P_n < 0.1\, fc'\, A_g$

$$UR_{Biax2} = \frac{M_{nx}}{M_{nox}} + \frac{M_{ny}}{M_{noy}} < 1.0$$

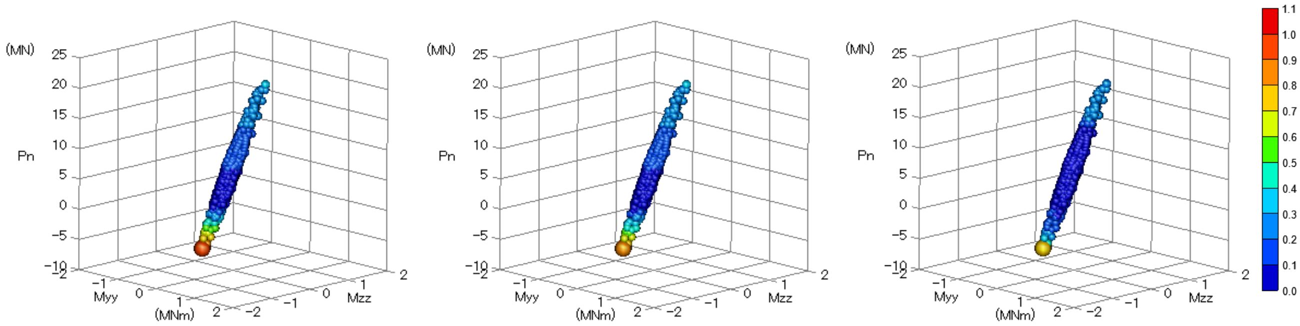
where:
M_{nx} = biaxial moment demand about x-axis
M_{ny} = biaxial moment demand about y-axis
M_{nox} = nominal uniaxial moment strength about x-axis for the applied axial load P_n
M_{noy} = nominal uniaxial moment strength about y-axis for the applied axial load P_n

The calculated URs are shown as contour plots of biaxial interaction diagrams in Fig. 9 to Fig.12 for column top and in Fig. 13 to Fig.16 for column bottom.



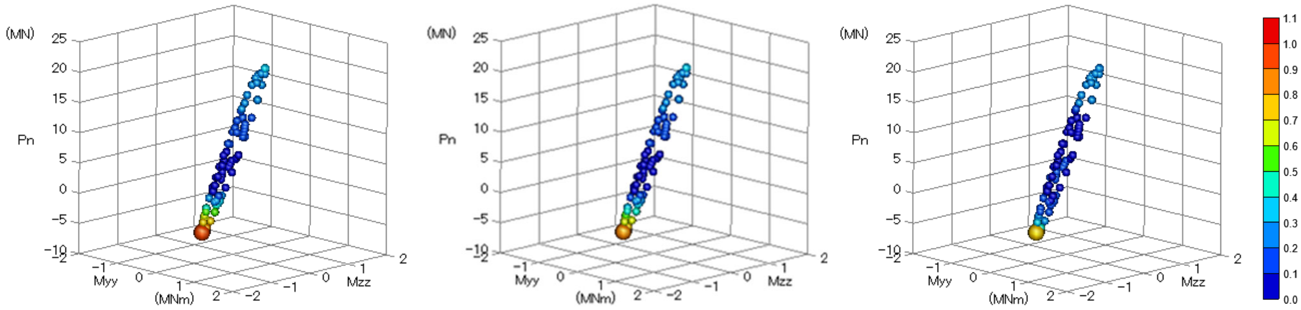
$$UR = \frac{a}{b} = \frac{\sqrt{P_n^{\,2} + M_n^{\,2}}}{\sqrt{\phi_y^{\,2} + \phi_x^{\,2}}}$$

Fig. 8 Uniaxial Bending Utilization Ratio



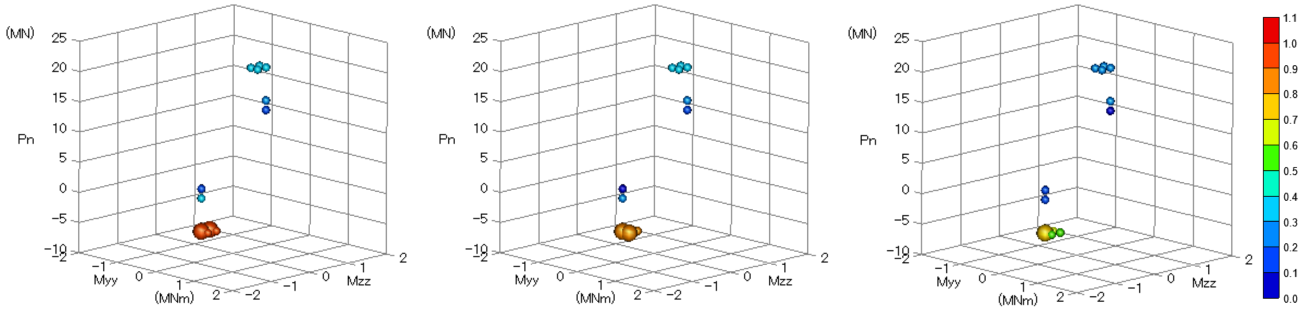
(a) Uniaxial UR_{yy} (b) Uniaxial UR_{zz} (c) Biaxial UR_{biax}

Fig. 9 UR at Column Top by Time History Calculation (N=4000)



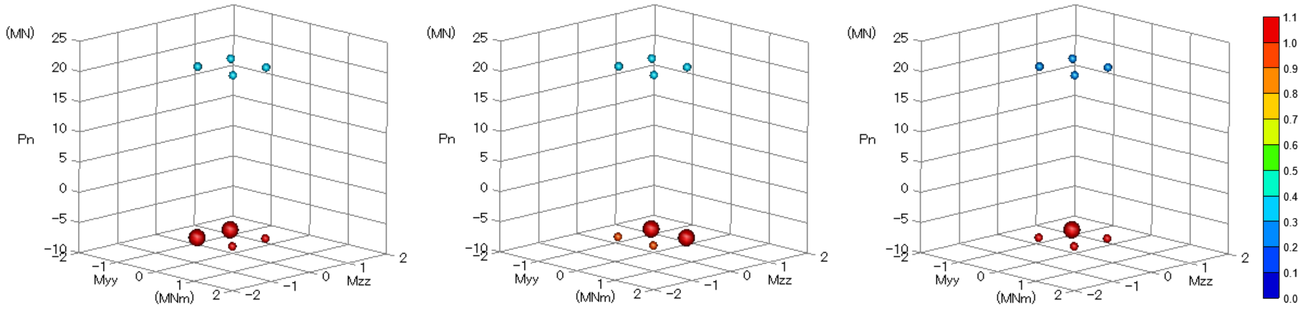
(a) Uniaxial UR_{yy} (b) Uniaxial UR_{zz} (c) Biaxial UR_{biax}

Fig. 10 UR at Column Top by Convex Hull Algorithm Extraction (N=83)



(a) Uniaxial UR_{yy} (b) Uniaxial UR_{zz} (c) Biaxial UR_{biax}

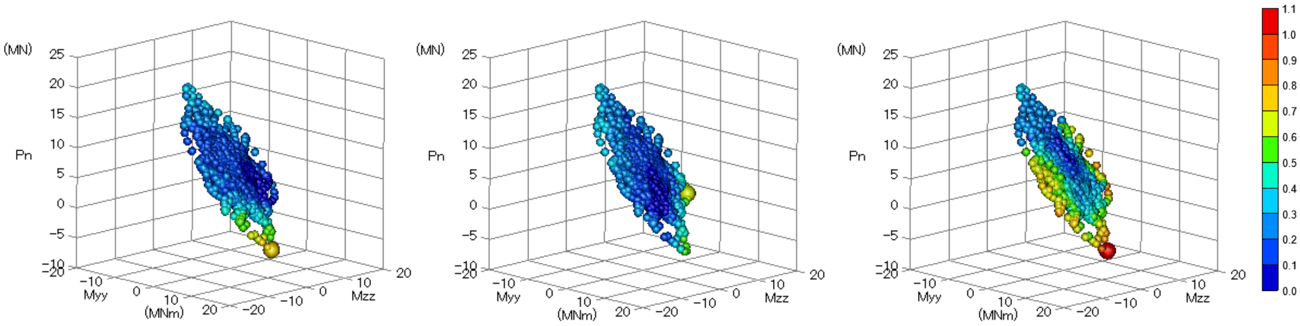
Fig. 11 UR at Column Top by Hexagonal Shape Extraction (N=12)



(a) Uniaxial UR_{yy} (b) Uniaxial UR_{zz} (c) Biaxial UR_{biax}

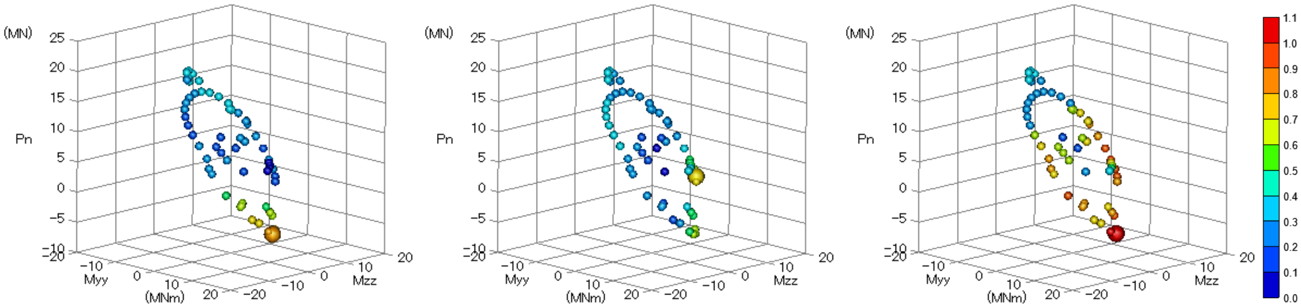
Fig. 12 UR at Column Top by Absolute Maximum Extraction (N=8)

Note: URs larger than 1.0 are shown in red. The maximum UR points are shown by large size.



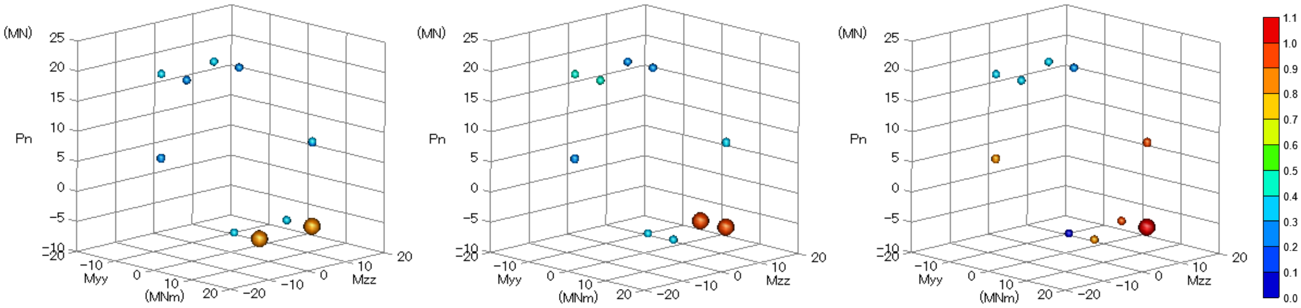
(a) Uniaxial UR_{yy} (b) Uniaxial UR_{zz} (c) Biaxial UR_{biax}

Fig. 13 UR at Column Bottom by Time History Calculation (N=4000)



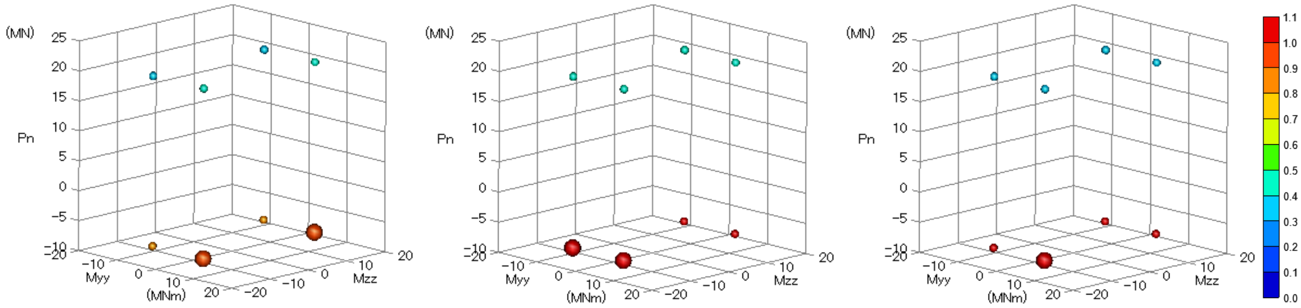
(a) Uniaxial UR_{yy} (b) Uniaxial UR_{zz} (c) Biaxial UR_{biax}

Fig. 14 UR at Column Bottom by Convex Hull Algorithm Extraction (N=63)



(a) Uniaxial UR_{yy} (b) Uniaxial UR_{zz} (c) Biaxial UR_{biax}

Fig. 15 UR at Column Bottom by Hexagonal Shape Extraction (N=12)



(a) Uniaxial UR_{yy} (b) Uniaxial UR_{zz} (c) Biaxial UR_{biax}

Fig. 16 UR at Column Bottom by Absolute Maximum Extraction (N=8)

Note: URs larger than 1.0 are shown in red. The maximum UR points are shown by large size.

Table 1 summarizes the maximum URs for each data extraction method.

It is confirmed from the results that the maximum URs of convex hull approach are identical to those of time history calculation. Therefore, the convex hull approach includes no conservativeness in data extraction process, and it can largely reduce the number of calculation points from the time history calculation.

The absolute maximum extraction method provides most conservative URs. Especially, the biaxial axial UR tends to become larger by this method.

The hexagonal shape extraction method provides the maximum URs closed to the time history calculation at the column top with only 12 extraction points. However, the calculated URs at the column bottom is more conservative because of the following reason. As seen in Fig.7, P-M diagrams at the column bottom show the broader spindle shape than those at the column top and the maximum axial force and the maximum bending moment do not occur simultaneously. In such case, the hexagonal shape approach provides more conservative URs.

Table 1 Comparison of Maximum Utilization Ratios

Section	Method	UR_{yy}	UR_{zz}	UR_{biax}	Number of points
Column Top	Time History	0.94	0.85	0.71	4000
	Convex Hull Algorithm	0.94	0.85	0.71	83
	Hexagonal Shape	0.94	0.85	0.73	12
	Absolute Maximum	1.08	1.03	5.71	8
Column Bottom	Time History	0.79	0.61	1.03	4000
	Convex Hull Algorithm	0.79	0.61	1.03	63
	Hexagonal Shape	0.87	0.96	1.75	12
	Absolute Maximum	0.95	1.04	1.99	8

5. Conclusions

To process the large number of element force data produced by the 3D-FEM analysis with the vast number of load combinations, an automated design tool for FE modelled reinforced concrete line elements has been developed in accordance with ACI 349. By applying this tool to section design of the column in a pilot model, the adequacy of the design data extraction methods from the time history element forces and moments were confirmed.

The proposed convex hull algorithm method provides the maximum URs identical to those by whole time history calculation. This approach includes no conservativeness in data extraction process, and it can largely reduce the number of calculation points from the time history calculation.

The other proposed hexagonal shape extraction method provides the maximum URs closed to the time history calculation for the element forces with sharp spindle shape P-M diagram. However, for the element forces which have broader spindle shape P-M diagram, it provides more conservative URs. As this approach uses only 12 extraction points and is possible to reduce the computation time largely, the further improvement should be added considering the shape of P-M diagram.

In this paper, a very simple pilot model with just one column with the symmetric rebar arrangement is utilized. By using the calculation function for asymmetric rebar arrangement developed in the design tool, the more rational rebar design can be achievable together with the convex hull algorithm method or the hexagonal shape extraction method.

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