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A STUDY ON COORDINATED EXPRESSION OF THE SEISMIC DIAGNOSIS SCORE AND ITS APPLICATION TO RETROFIT REINFORCEMENT PROJECTS UNDER COST CONTROL FOR JAPANESE TIMBER HOUSES

Daisuke Shimizu[1], Chikako Tabata[2], Yoshito Tomioka[3]

ABSTRACT: The seismic diagnosis score for a conventional timber house in Japan is normally calculated as the ${}_{ed}Q_p/Q_r$ ratio. This study presents its coordinated expression as (Q_r, ${}_{ed}Q_p$), making it possible to depict the individual effect and contribution of each specification employed in a retrofit reinforce project as a whole. This method could be used to knockdown not only the change in the force capacity of the whole building but also the level of independent elements, such as a wall or roof. Combining this method to add cost dimension to the coordination as (Q_r, ${}_{ed}Q_p$, *cost factor*) may be feasible in serving as a rational design tool that can achieve a better cost-performance in retrofit design practice. Four factors exist for each of the individual elements of retrofitting performed in seismic retrofit reinforcement, that is, required strength, potential strength, cost for applied element, and cost for eliminated element. In this study, a theoretical method is used to express each factor in a unified manner. This possibility is confirmed by applying the method to real retrofit reinforce design experiences obtained in Mie Prefecture, Japan.

KEYWORDS: Structural design method, Construction cost, Japanese conventional timber house

1 INTRODUCTION

This study explains the idea of the coordinated expression of the seismic diagnosis score and discusses its possible applications as a rational tool in designing retrofit reinforce projects of Japanese conventional timber houses. Its feasibility is estimated by applying it to real design experiences obtained in Mie Prefecture, Japan.

2 COORDINATED EXPRESSION OF THE SEISMIC DIAGNOSIS SCORE

2.1 BASIC THEORY

The seismic diagnosis score, used for the retrofit reinforcement of timber houses is calculated as follows:

$$S = {}_{ed}Q_p/Q_r \tag{1}$$

where S (non-dimensional) = seismic diagnosis score, ${}_{ed}Q_p$ (kN) = potential strength; lateral force capacity of the structure and Q_r (kN) = required strength; necessary lateral resistance led from the weight of supported building part.

The index = 1.0 means that the structure achieves minimum seismic safety. Although this approach may be good for a simple representation of the safety degree in a single number, it lacks the guidance ability for conducting a design rationally and is not a reinforcement cost consideration method. This study proposes its coordinated expression as [1]:

$$\vec{S} = (Q_r,\ {}_{ed}Q_p) \tag{2}$$

where $\vec{S}$ (non-dimensional) = coordinated expression of the seismic diagnosis score.

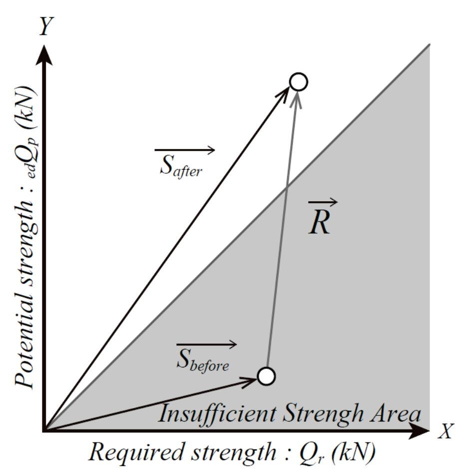

Figure 1: *Performance plot of the required strength vs potential strength*

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Figure 1 presents a two-dimensional (2D) theoretical coordination system. On this surface, the seismic performance of the existing building to be reinforced is plotted as "before," while the achieved performance is plotted as "after." Accordingly, the performance improvement due to reinforcement is expressed as a vector connecting both as $\vec{R}$.

$$\vec{R} = \overrightarrow{S_{after}} - \overrightarrow{S_{before}} \quad (3)$$

The minimum safety (i.e., Index = 1.0) is now expressed as a line of $Y = X$. The reinforcement design attempt is recognized to extend the reinforcement vector from "before" to "after," which is beyond the line.

Figure 2 shows breakdown into successive applications of reinforce elements. This case involves two elements, namely $\overrightarrow{E_1}$ and $\overrightarrow{E_2}$, representing two independent reinforcements that constitute the total. Reinforcement (E_1) is normally a combined elimination of a certain existing element (e_1') and an application of another specified element (e_1) that is structurally superior.

$$\vec{R} = \sum \vec{E} \quad (4)$$

$$\vec{E} = \vec{e} - \overrightarrow{e'} \quad (5)$$

where $\vec{E}$ = the specification vector representing the score transition due to the reinforcement of each element, $\vec{e}$ = the performance vector of the applied substitute element and $\overrightarrow{e'}$ = the performance vector of the eliminated existing element.

Using this expression, we understand the several observations of total reinforcements from all the structural elements employed in the design.
Figure 3 shows the further breakdown and characteristic vector of the element. The performance vector $\vec{e}$ of the structural element is normally cumulative according to its scalar amount (a: length (m) or area (m^2), typically). Therefore, it can be described as

$$\vec{e} = a \times \vec{p} \quad (6)$$

$$\vec{p} = (p_r, p_p) \quad (7)$$

where a (m and m^2) = scalar amount of the element, $\vec{p}$ = characteristic vector, p_r (kN/m, kN/m^2) = required strength of the element per scalar and p_p (kN/m, kN/m^2) = potential strength of the element per scalar.

2.2 COMBINED WITH THE COST DIMENSION

We consider the reinforcement design from a wider perspective by combining this method with a cost factor as an independent dimension. In Figure 4, we express this in a three-dimensional (3D) coordinate system combined with a cost factor. There are costs to apply the element (c_{ap}) and eliminate the element (c_{el}), which are different values.

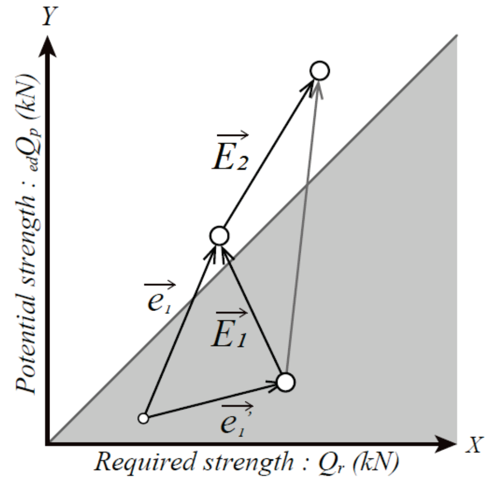

Figure 2: *Breakdown into successive applications of reinforce elements*

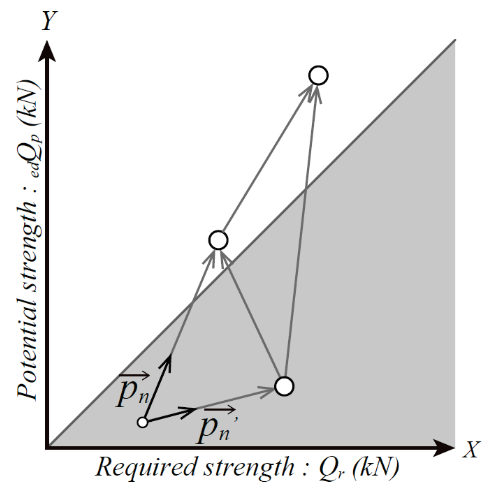

Figure 3: *Characteristic vector of the element*

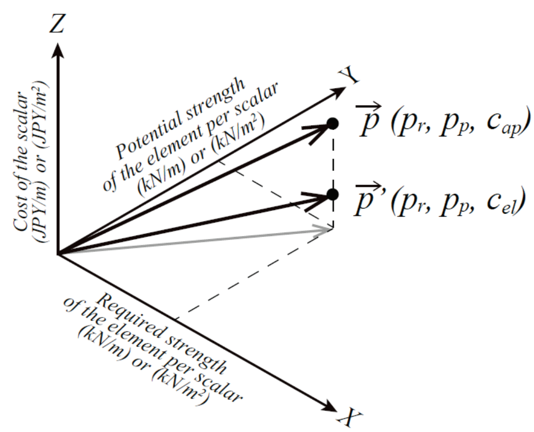

Figure 4: *Characteristic vector of the coordinate system combined with a cost dimension in a three-dimensional coordinate system*

We consider that it would be convenient to unify representation the four factors for the calculation. Therefore, we express the characteristic vector using a four-dimensional column vector as follows:

$$\vec{p} = \begin{pmatrix} p_r \\ p_p \\ c_{ap} \\ c_{el} \end{pmatrix} \tag{8}$$

where c_{ap} (JPY/m or JPY/m^2) = the cost per scalar for the applied element and c_{el} (JPY/m or JPY/m^2) = the cost per scalar for the eliminated element.

The characteristic vector can represent the element characteristics unifacially for both application and elimination. For the elimination, we multiply the characteristic vector by the elimination factor (F_{el}) as follows:

$$\begin{aligned} \overrightarrow{p'} &= F_{el} \times \vec{p} \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \end{pmatrix} \begin{pmatrix} p_r \\ p_p \\ c_{ap} \\ c_{el} \end{pmatrix} = \begin{pmatrix} p_r \\ p_p \\ -c_{el} \\ -c_{ap} \end{pmatrix} \end{aligned} \tag{9}$$

where $\overrightarrow{p'}$ = characteristic vector of the eliminated element and F_{el} = elimination factor.

c_{ap} and c_{el} are transposed by multiplying by the elimination factor. Therefore, we can calculate the required strength in the first row, the potential strength in the second row, and the cost of application or elimination whichever is chosen in the third row.

The total reinforcement is expressed as the synthesis of all the above:

$$\vec{R} = \sum \vec{E} = \sum_n a_n (\overrightarrow{p_n} - \overrightarrow{p_n{'}}) \tag{10}$$

where a_n (m, m^2) = scalar of the nth characteristic element, $\overrightarrow{p_n}$ = nth characteristic vector of the applied substitute element and $\overrightarrow{p_n{'}}$ = nth characteristic vector of the eliminated existing element.

3 TRIAL ESTIMATIONS OF THE CHARACTERISTIC VECTOR

We explain herein the method for estimating the characteristic vector. A retrofit reinforcement is normally made by enforcing walls and changing roof materials.
For the walls, the characteristic strength and weight of materials are recognized by dividing the horizontal length (m) while fixing the height as 2.8 m.
For the roofs, the characteristic amounts were considered by dividing the surface (m^2).

A) Wall
The characteristic vectors of walls are calculated as follows:

1) The extra potential strength/length factor was taken from the book entitled "*MOKUZOJYUTAKU NO TAISHINSHINDAN TO HOKYOHOHO* (Seismic Diagnosis and Reinforcement on Timber Houses)" from Ref. [2]. Ref. [2] provides guidelines and explanations on the seismic diagnosis and reinforcement methods for Japanese timber houses.

2) The extra strength per length factor is calculated as follows:

$$p_r = 0.2 \times w \times g \times h \tag{11}$$

where *0.2* (non-dimensional) = theoretical coefficient to make the seismic force consistent at the time of a major earthquake with the evaluated value of the element's bearing capacity, w (kg/m^2) = weight of the specified wall per unit surface [3], g (m/s^2) = gravity acceleration and h (m) = height of the specified wall (i.e., 2.8 m is widely used).

3) The cost factors were taken from the recent report so-called "*BUKKABAN.*" In Japan, "*SEKISAN SHIRYO"* [4, 5] and "*SEKISAN POKETTO TETYO"* [6] are the most popular publishers reporting the current construction and material costs of specified construction in each region. We prioritize Ref. [4] here.
We gathered information on the cost estimation from practitioners to fit the raw information of the combination of materials and construction for retrofit projects.

Figure 5 shows example characteristic vectors of the wall estimated by the foregoing.

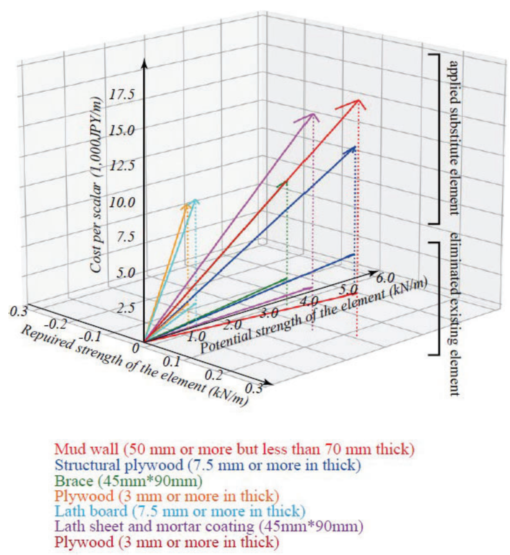

Figure 5: *Example characteristic vectors of the wall*

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B) Roof

The characteristic vectors of roofs are calculated as follows:

1) The roof case is much simpler. Roofs normally do not affect strength accumulation but affect the weight reduction through the changing of roof materials. Therefore, the p_p is zero.

2) The extra strength per length factor is calculated as

$$p_r = 0.2 \times w \times g \tag{12}$$

where *0.2* (non-dimensional) = theoretical coefficient that makes the seismic force at the time of a major earthquake with the evaluated value of the element's bearing capacity, w (kg/m^2) = weight of the specified wall per unit surface [3], and g (m/s^2) = gravity acceleration.

3) The cost factors were taken from the recent report, "*BUKKABAN*."

Figure 6 shows example characteristic vectors of the roof estimated by the foregoing.

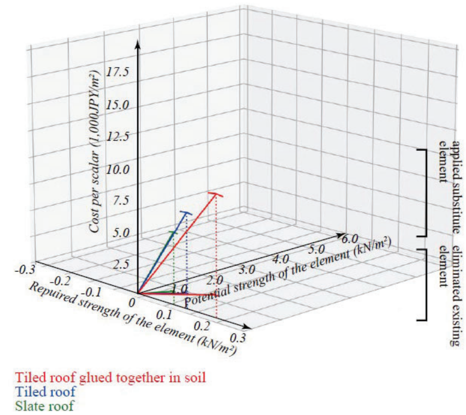

Figure 6: *Example characteristic vectors of the roof*

4 HOW TO USE THE THEORY IN THE STRUCTURAL RETROFIT DESIGN

4.1 COMBINED WITH THE CHARACTERISTIC VECTOR FOR PRACTICAL USE

There are many frequently used reinforcement methods at timber houses. Therefore, synthesizing vectors of application and elimination for each element is convenient (Figure 7). We define herein the element reinforcement vector $\overrightarrow{P_{syn}}$ calculated as follows:

$$\overrightarrow{P_{syn}} = \vec{p} - \overrightarrow{p'} = \begin{pmatrix} p_r \\ p_p \\ c_{ap} \\ c_{el} \end{pmatrix} - \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \end{pmatrix} \begin{pmatrix} p_r \\ p_p \\ c_{ap} \\ c_{el} \end{pmatrix} \tag{13}$$

where $\overrightarrow{P_{syn}}$ = element reinforcement vector.

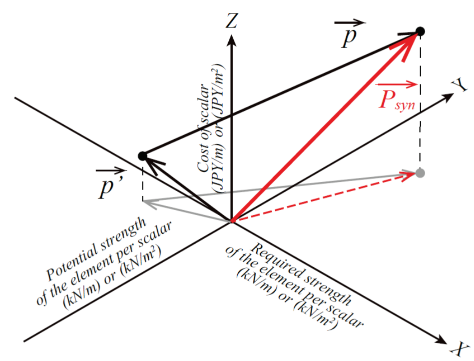

Figure 7: *Synthesizing vectors of application and elimination*

A) Wall

Figure 8 shows an example of the element reinforcement vectors of the wall. These vectors are extracts frequently used in the reinforcement plans gathered from practitioners. We categorize the wall reinforcement work as follows:

1) Insertion: Insert a new wall where no wall exists.
2) Addition: Add an element to the existing wall.
3) Substitution: Substitute a structurally inferior existing wall with a structurally superior new wall.

Insertion uses $\vec{p}$ as is. Addition utilizes $\vec{p}$ of the added element only as is. Substitution is a combination of the characteristic vector of the eliminated existing structurally inferior element ($\overrightarrow{p'}$) and the characteristic vector of the applied structurally superior substitute element ($\vec{p}$).

Even when multiple elements are combined (e.g., a combination of structural plywood and brace), each characteristic vector can be combined and considered as an element reinforcement vector.

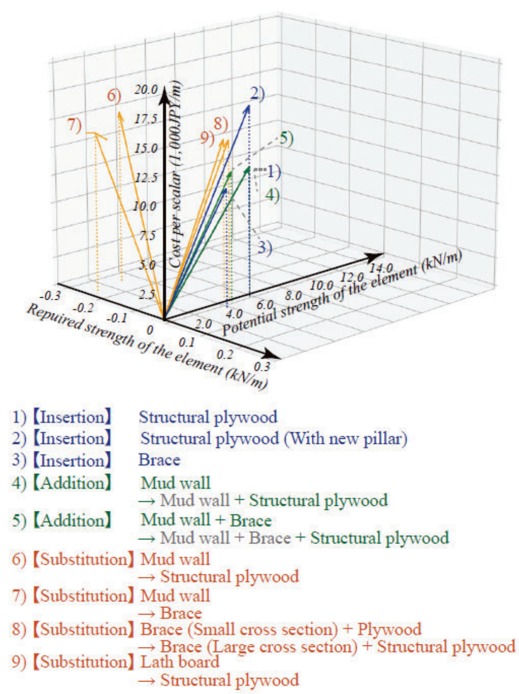

Figure 8: *Example of the element the reinforcement vectors of the wall*

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B) Roof

Figure 9 shows an example of the element reinforcement vectors of the roof. For the roof, the heavy material roof is eliminated and substituted with a lighter roof. This can be considered a substitution for the wall case.

4.2 SELECTING THE MOST EFFECTIVE REINFORCEMENT

In seismic reinforcement, the required strength is reduced, for example, by changing the roof materials, while the potential strength is increased, for example, by reinforcing the walls. We consider the case in which the reinforcement method effectiveness is examined only by considering the transition between the required and potential strengths (i.e., using a 2D coordinate system). We can determine that the effective reinforcement is a scalar of inner product projected in the direction to the line $Y = -X$ (Figure 10) because it expresses a great effect on reduces the required strength and increases the potential strength. Therefore, when multiple reinforcement methods are considered, the most effective reinforcement approach is the one that result in the largest inner product, which can be calculated as follows.

$$\left(-\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\right) \cdot \vec{P} = Max \tag{14}$$

By adopting our explained 3D coordinate system, we can consider the reinforcement cost in addition to the performance improvement (Figure 11). The reinforcement beyond the $Y = X$ perpendicular line must eliminate the existing elements and apply new ones. This means that both elimination and application costs will be required as the reinforcement cost. In some cases, the reinforcement vectors considered as inefficient in a 2D coordinate system (i.e., the reinforcement method that increases p_r and p_p because it does not require eliminate element.) may be optimal from a cost-effective standpoint.

4.3 VISUAL REPRESENTATION OF PERFORMANCE IMPROVEMENT ON CAD SCREEN

We believe that our method can be very useful in practical design works. The software [7] used for seismic reinforcement design is widely used in Japan. By combining our method with this software, the performance improvement caused by the element changes can be displayed on the same screen in real time (Figure 12). We can assume that the 3D theory is maintained here. However, the transition of Q_r and $_{ed}Q_p$ are examined in a 2D coordinate system with the change of the method of display. The reinforcement cost is provided as an accumulation on a separate adjacent graph.

The seismic reinforcement design is performed under various constrained conditions, such as the house layout and a limited budget. The ability of designers to watch the optimal cost efficiency in each case can be used as a rational design tool.

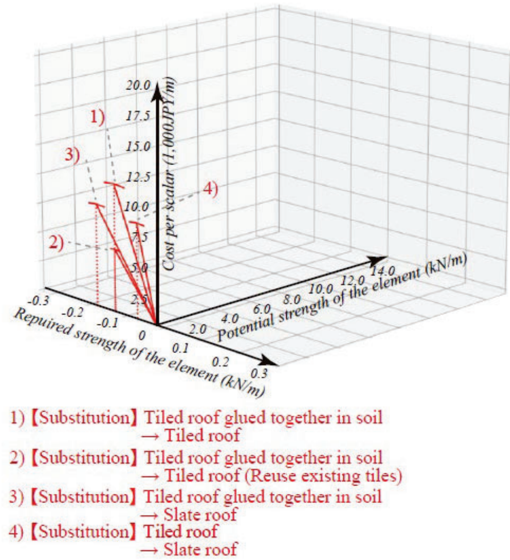

Figure 9: *Example of the element the reinforcement vectors of the roof*

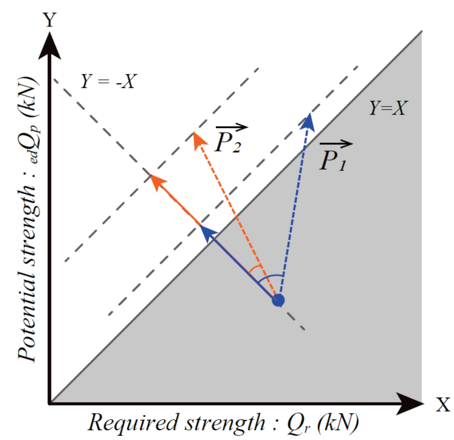

Figure 10: *Consideration for the effective reinforcement method in a 2D coordinate system*

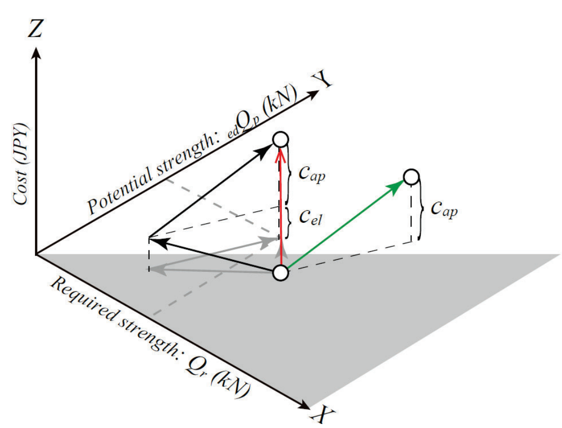

Figure 11: *Consideration for the effective reinforcement method in a 3D coordinate system*

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5 CONCLUSIONS

This study explained the method of the coordinated expression of the seismic diagnosis score, derived relevant definitions, and demonstrated how to use the theory in practical design works to enable designers to observe cost efficiency during the design phase.

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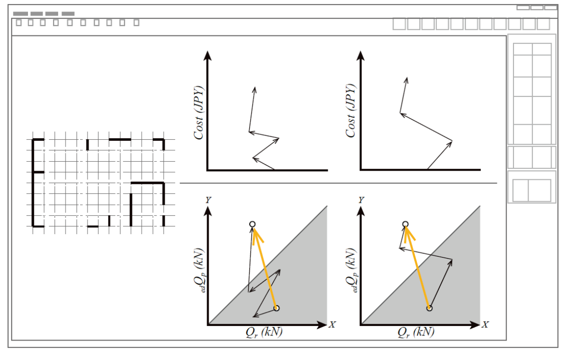

Figure 12: *Real-time display of performance improvement caused by the element changes on the screen*

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