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Optimum Location of Outrigger-belt Truss in Tall Buildings Based on Maximization of the Belt Truss Strain Energy

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ABSTRACT

In this paper, based on maximizing the outrigger-belt truss system's strain energy, a methodology for determining the optimum location of an outrigger-belt truss system is presented. Tall building structures with combined systems of framed tube, shear core and outrigger-belt truss system are modeled using continuum approach. In this approach, the framed tube system is modeled as a cantilevered beam with box cross section. The effect of outrigger-belt truss and shear core system on framed tube's response under lateral loading is modeled by a rotational spring at the outrigger-belt truss location. Optimum location of this spring is obtained when energy absorbed by the spring is maximized. For this purpose, first derivative of the energy equation with respect to spring location as measured from base of the structure, is set to zero. Optimum location for outrigger-belt truss system is calculated for three types of lateral loadings, i.e. uniformly and triangularly distributed loads along structure's height, and concentrated load at top of the structure. Accuracy of the proposed method is verified through numerical examples. The results show that the proposed method is reasonably accurate.

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1. INTRODUCTION

In recent decades, outrigger-belt truss systems have been widely utilized in tall buildings for decreasing structure's deformation and increasing its resistance to lateral loads. The outrigger and belt truss systems connect exterior columns to the interior shear core. Consequently, the exterior columns and belt truss system resist the rotation of central shear core and decrease the lateral deformation as well as bending moment at base of the structure [1-11]. Hence, knowing the optimum location of outrigger and belt truss systems correctly is crucial in effectively decreasing deformation and moments of a tall structure. Many researchers have studied the optimum location of an outrigger-belt truss system in a tall structure subjected to lateral loading based on the decrease in lateral displacement at the top of the structure. Smith and Salim [12] developed formulae for estimating the optimum levels of outriggers with the objective of minimizing the drift in outrigger braced buildings. These formulae are developed by applying multiple regression analysis to the results of relatively complex compatibility analyses of structures with up to four outriggers. Rutenberg and Tal [13] presented the results of an investigation on drift reduction in uniform and non-uniform belted structures with rigid outriggers under several lateral load distributions which are likely to be encountered in practice. Zhang et al. [14] carried out a case study to analyze the horizontal top deflection and the mutation of restraining moments caused by variations in outrigger location. Bayati et al. [15] presented the results of an investigation on drift reduction in uniform belted structures with rigid outriggers through analysis of a sample structure that was built at Tehran's Vanak Park. Gerasimidis et al. [16] calculated optimum outrigger locations for a framed high rise structure reinforced by shear core wall and outrigger systems subjected to wind loading. Optimum location of the outrigger was calculated based on drift control criteria and balance of moments transferred by the outriggers to exterior columns. Rahgozar and Sharifi [17] presented a mathematical model for the combined system of framed tube, shear core and outrigger-belt truss with the objective of determining the optimum location of belt

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truss along building's height. The effect of belt truss and shear core on a framed tube was modeled as a concentrated moment applied at belt truss location. Optimum location of the belt truss was obtained by minimizing the deflection at top of the structure. Fawzia and Fatima [18] compared deflection variations while using up to three belt truss and outrigger systems for the same height. Similar studies were conducted by Fawzia et al. [19], their investigations were based on deflection control and frequency optimization while using belt truss and outrigger systems for different building heights.

Control of deformation is an important criterion considered in building codes; another criterion is the control of stresses so not to exceed a certain value [20-22]. Naturally, simultaneous consideration of both criteria should yield better results. Energy criterion is another reliable criterion in engineering problems. Energy which is equivalent to product of forces and displacements is a more comprehensive criterion than displacement or stress by themselves when computing the optimum location of outrigger-belt truss system in a tall building structure.

In this paper, optimum location of outrigger-belt truss system is obtained using energy criterion. A tall building structure with combined system of framed tube, shear core and outrigger-belt truss system is modeled using continuum approach. Here the framed tube system is modeled as a cantilevered beam with box cross section [23-25]. Effect of outrigger-belt truss and framed tube systems on shear core under lateral loading is modeled by a rotational spring placed at outrigger-belt truss location [10, 11]. Then, the optimum location of the spring is obtained when the energy absorbed by the spring became maximum. For this purpose, derivative of the energy functional with respect to location of the spring as measured from base of the structure is set to zero. Accuracy of the proposed method is verified through numerical examples.

2. MODELLING THE COMBINED SYSTEM OF FRAMED TUBE, SHEAR CORE AND OUTRIGGER-BELT TRUSS

A tall building structure with combined system of framed tube and shear core subjected to lateral loading can be modeled as a cantilevered beam (see Figure 1) [26].

Outrigger-belt truss system under lateral loading acts as a rotating spring and causes changes in the moment distribution (see Figure 2) [27]. Its role in the structure is to reduce the moment at structure's base and the displacement at structure's top.

It is important to know the optimum location of an outrigger and belt truss system so to design the largest possible reduction in the base moment and displacement at structure's top. Most research studies determine the optimum location of outrigger and belt truss system in tall buildings based on displacement criterion at top of the structure which have led to valuable findings. As mentioned earlier, the purpose of this research is to obtain optimum location of outrigger and belt truss systems by using energy criterion. Work done by external loads is stored as strain energy in structural members when the structure is subjected to external lateral loads. A portion of this energy is stored by the outrigger-belt truss (or equivalent spring as Figure 2). Hence, the optimum location of outrigger can be calculated when energy absorbed by the rotational spring model becomes maximum.

Strain energy of the equivalent spring is:

$$E = \frac{1}{2} K\theta^2 \tag{1}$$

where θ and K are rotation and stiffness of the equivalent spring. In finding optimum location of the equivalent spring, first derivative of the energy equation with respect to location of the spring as measured from base of the structure (a) should be zero (i.e. $dE/da = 0$).

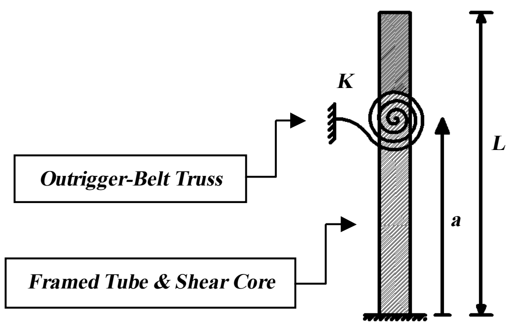

Figure 1. Combined system of framed tube, shear core and outrigger-belt truss

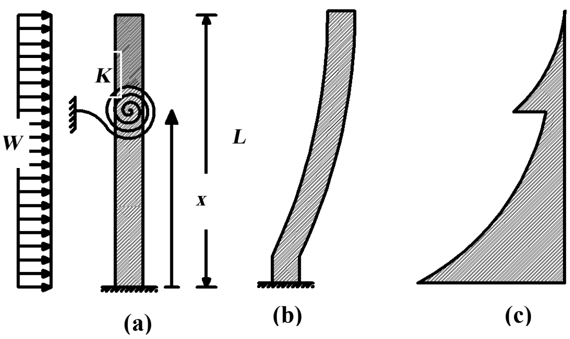

Figure 2. Behavior of combined system under lateral loads (a) shear core and belt truss, (b) displacement and (c) moment diagram

For this purpose θ and K should be presented as a function of parameter a. θ is related to loading type, i.e, three types of lateral loading, as uniformly distributed load and triangularly distributed load along the height of the structure and concentrated load at top of the structure.

While analyzing this structure several assumptions were made: *a*) connection between shear core and belt truss is fixed, *b*) connection between exterior columns and belt truss is fixed, *c*) belt truss is rigid, *d*) changes in axial stiffness of exterior columns and also changes in the moment of inertia for shear core along structure's height are neglected.

3. CALCULATION OF THE OPTIMUM LOCATION FOR OUTRIGGER-BELT TRUSS SYSTEM UNDER UNIFORMLY DISTRIBUTED LATERAL LOADING

As mentioned earlier, a structure with combined system of framed tube and shear core can be modeled as cantilevered beam with moment of inertia of the shear core. Effects of outrigger and belt truss systems on the primary structure can be modeled via a rotational spring placed at outrigger-belt truss location, somewhere along structure's height. In next sections, the spring model is presented.

3. 1. Rotation of Equivalent Spring In the model shown in Figure 3, the structure is subjected to uniformly distributed lateral load *W*; and rotation of the beam at location *a* is measured by angle θ_a.

Based on superposition principle, θ_a is:

$$\theta_a = \theta_{a,1} + \theta_{a,2} \tag{2}$$

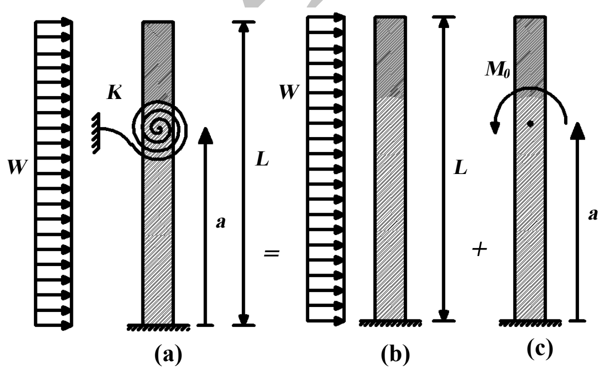

Figure 3. (a) Restrained cantilever beam with rotational spring under uniformly distributed loading, (b) cantilever beam under uniformly distributed loading and (c) cantilever beam with concentrated moment at spring location

where $\theta_{a,1}$ is the rotation due to lateral load applied to a beam without the rotational spring and $\theta_{a,2}$ is the rotation due to moment M_0 generated by the rotational spring (Figure 3). To calculate $\theta_{a,1}$, the rotation of a section at distance *x* from base of the structure is given by Figure 3b where $\theta_{a,1}$ is the rotation due to lateral load applied to a beam without the rotational spring and $\theta_{a,2}$ is the rotation due to moment M_0 generated by the rotational spring (Figure 3). To calculate $\theta_{a,1}$, the rotation of a section at distance *x* from base of the structure (Figure 3b) is given by:

$$\theta_{x,1} = \theta_0 + \frac{1}{EI}\int_0^x M_x dx \tag{3}$$

Since origin of the coordinates is placed at structure's base, hence θ_0 is zero.

M_x of the beam in Figure 3a is:

$$M_x = WLx - \frac{WL^2}{2} - \frac{Wx^2}{2} \tag{4}$$

Hence:

$$\theta_{x,1} = \frac{1}{EI}\left(\frac{WLx^2}{2} - \frac{WL^2 x}{2} - \frac{Wx^3}{6}\right) \tag{5}$$

Therefore $\theta_{a,1}$ becomes:

$$\theta_{a,1} = \frac{1}{EI}\left(\frac{WLa^2}{2} - \frac{WL^2 a}{2} - \frac{Wa^3}{6}\right) \tag{6}$$

Angular rotation $\theta_{a,2}$ due to moment M_0 is computed using expression for $\theta_{x,2}$ i.e.

$$\theta_{x,2} = \frac{1}{EI}\int_0^x M_x dx + \theta_0 \tag{7}$$

Hence θ_2 at location *a* is:

$$\theta_{a,2} = \frac{M_0}{EI} \tag{8}$$

Since M_0 is:

$$M_0 = K\theta_a \tag{9}$$

then

$$\theta_{a,2} = \frac{K\theta_a a}{EI} \tag{10}$$

Placing Equations (6) and (10) into Equation (2) yields:

$$\theta_a = \frac{\dfrac{WLa^2}{2} - \dfrac{WL^2 a}{2} - \dfrac{Wa^3}{6}}{EI - aK} \tag{11}$$

which is the rotation of beam at outrigger-belt truss location, as building is subjected to uniformly distributed lateral loading.

3. 2. Stiffness of the Equivalent Spring As mentioned before, outrigger-belt truss behaves rigidly and it is connected to exterior columns through hinges. As shown in Figure 4, moment $M_0 = K\theta_a$ can be replaced by a couple force applied at exterior columns:

$$M_0 = Fd \tag{12}$$

where F is the axial force in exterior columns and d is the distance between these columns.

Assuming that cross sectional area of exterior columns doesn't change along structure's height, then axial force F is:

$$F = \frac{AE\delta}{a} \tag{13}$$

where E is modulus of elasticity of the structure and δ is axial deformation of exterior columns. Since rotation angle of the belt truss is small, then one can conclude:

$$\theta_a = \frac{2\delta}{d} \tag{14}$$

Equations (12-14) yield:

$$K = \frac{AEd^2}{2a} \tag{15}$$

Note from Equation (15) that the stiffness of equivalent spring, K, is inversely proportional to the location of the spring, a, as measured from structure's base. From Equation (1) first derivative of energy equation with respect to spring location, a, is set to zero (i.e. $dE/da = 0$) or,

$$\theta_a \frac{dK}{da} + 2K\frac{d\theta_a}{da} = 0 \tag{16}$$

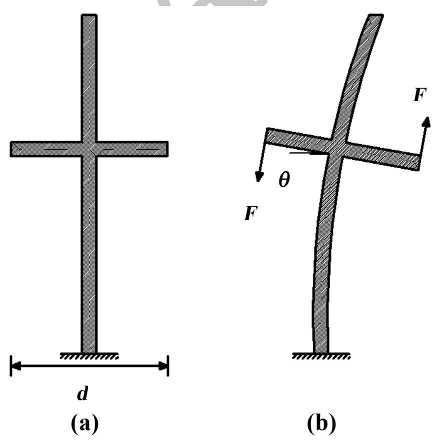

Figure 4. Couple force applied to exterior columns axially, (a) undeformed shape of outrigger-belt truss and column and (b) deformed shape of outrigger-belt truss and column

Equation (16) can be used for calculating the optimum location of outrigger-belt truss system along structure's height. Optimum location of the outrigger-belt truss system can be obtained by substituting θ_a and K from Equations (11) and (15) into Equation (16) and solving for a. Hence, the optimum location of outrigger-belt truss system for uniformly distributed loading is calculated from Equation (16) as:

$$a = 0.441L \tag{17}$$

This is the optimum location for outrigger-belt truss system along structure's height, as obtained using energy criterion. The structure is subjected to uniformly distributed load along its height. In the following sections, optimum location of outrigger-belt truss will be calculated for structures subjected to triangularly distributed loading or concentrated load applied at top of the structure. Since value of K is independent of loading type, for these two types of loading, θ is first calculated and then it is placed into Equation (16) to determine the optimum location.

4. OPTIMUM LOCATION OF OUTRIGGER-BELT TRUSS SYSTEM SUBJECTED TO TRIANGULARLY DISTRIBUTED LOADING

4. 1. Rotation of the Equivalent Spring According to Figure 5, when the structure is subjected to triangularly distributed lateral load, then the rotation angle of the beam at location a is defined as θ_a, Equation (2). Rotation $\theta_{a,1}$, of a section at distance x from base of the structure (Figure 5b) can be written as:

$$\theta_{x,1} = \theta_0 + \frac{1}{EI}\int_0^x M_x dx \tag{18}$$

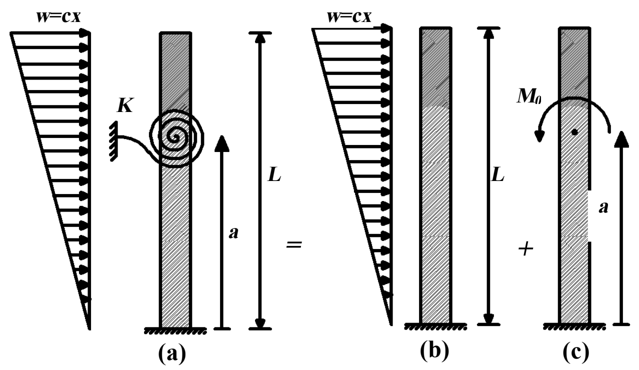

Figure 5. (a) Restrained cantilever beam with rotational spring under triangularly distributed loading, (b) cantilevered beam under triangularly distributed loading and (c) cantilevered beam under concentrated moment at spring location

Equation (18) is the same as Equation (3). Since the origin of Cartesian coordinates is selected at base of the structure, $\theta_0 = 0$, M_x for Figure 5a is:

$$M_x = \frac{cL^2 x}{2} - \frac{cL^3}{3} - \frac{cx^3}{6} \tag{19}$$

Substituting Equation (19) into Equation (18) yields:

$$\theta_{x,1} = \frac{1}{EI}\left(\frac{cL^2 x^2}{4} - \frac{cL^3 x}{3} - \frac{cx^4}{24}\right) \tag{20}$$

Therefore value of θ_1 at $x = a$ becomes:

$$\theta_{a,1} = \frac{1}{EI}\left(\frac{wLa^2}{2} - \frac{wL^2 a}{2} - \frac{wa^3}{6}\right) \tag{21}$$

$\theta_{a,2}$ due to moment M_0, is obtained in the same manner as for the uniformly distributed load, i.e.

$$\theta_{a,2} = \frac{K\ \theta_a\ a}{EI} \tag{22}$$

Substituting Equations (21) and (22) into Equation (2) yields:

$$\theta_a = \frac{\frac{cL^2 a^2}{4} - \frac{cL^3 a}{3} - \frac{ca^4}{24}}{EI - ak} \tag{23}$$

Optimum location of outrigger-belt truss system for triangularly distributed loading can be calculated by substituting Equations (15) and (23) into characteristic Equation (16) and solving for *a*, hence,

$$a = 0.490L \tag{24}$$

This value is the optimum location of outrigger-belt truss system along structure's height, as obtained using energy criterion. The structure is subjected to triangularly distributed load along its height.

5. OPTIMUM LOCATION OF OUTRIGGER-BELT TRUSS SYSTEM UNDER CONCENTRATED LOAD APPLIED AT TOP OF THE STRUCTURE

5. 1. Rotation of the Equivalent Spring According to Figure 6, if the structure is subjected to concentrated lateral load *P* at its top, then rotation angle of beam at location *a* is defined as θ_a, Equation (2). In calculating $\theta_{a,1}$, rotation of a section at distance *x* from base of the structure is used (Figure 6b) i.e:

$$\theta_{x,1} = \theta_0 + \frac{1}{EI}\int_0^x M_x dx \tag{25}$$

Equation (25) is the same as Equation (3). Since origin of the coordinates is selected at structure's base, $\theta_0 = 0$. M_x in Figure 6a is:

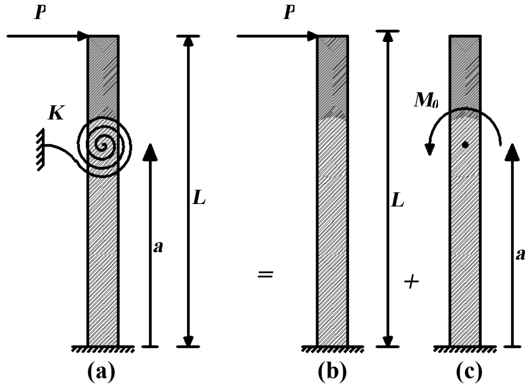

Figure 6. (a) Restrained cantilever beam with rotational spring under concentrated load at top of the structure, (b) cantilever beam under concentrated load at top of the structure and (c) cantilever beam under concentrated moment at spring location

$$M_x = Px - PL \tag{26}$$

Therefore value of $\theta_{x,1}$ at $x = a$ becomes:

$$\theta_{a,1} = \frac{1}{EI}\left(\frac{Pa^2}{2} - PLa\right) \tag{27}$$

$\theta_{a,2}$ due to moment M_0 is obtained in the same way as for the uniformly loaded case, i.e:

$$\theta_{a,2} = \frac{K\ \theta_a\ a}{EI} \tag{28}$$

Substituting Equations (27) and (28) into Equation (2) yields:

$$\theta_a = \frac{\frac{Pa^2}{2} - PLa}{EI - aK} \tag{29}$$

Optimum location of outrigger-belt truss system for the case of concentrated load at top of the structure can be calculated by substituting Equations (15) and (29) into characteristic Equation (16) and solving for *a* to obtain,

$$a = 0.667L \tag{30}$$

This value is the optimum location of outrigger-belt truss system along structure's height, as obtained using energy criterion. The structure is subjected to concentrated load at its top.

6. NUMERICAL INVESTIGATION AND COMPARISION OF RESULTS

In this section, results obtained from the proposed method are compared to previously published results and results from computer analyses. This comparison is indicative of the accuracy and simplicity of the proposed method.

6. 1. Comparison with Published Work In a paper by Rahgozar and Sharifi [17], closed form solution for the optimum outrigger-belt truss location was derived based on displacement minimization. Writing the compatibility equation for rotation at *x*, which is the location of outrigger-belt truss as measured from base of the structure, lateral displacement at top of the structure can be obtained. Optimum location of outrigger-belt truss is where the lateral displacement is minimum at that location. This is obtained by differentiating the displacement equation with respect to *x* and equating to zero. Here the building is modeled as a cantilevered beam with a spring placed at a distance *x* from the base, where outrigger-belt truss is located as shown in Figure 2. The optimum location obtained for three types of lateral loadings such as concentrated, uniform and triangular distributions are listed in Table 1.

6. 2. Comparison of Results by Proposed Method and Computer Analysis In this case a 30-story steel framed structured building is analyzed using SAP2000; software and optimum location of outrigger-belt truss is calculated. The results are then compared to those obtained from the proposed method. Results are listed in Table 2 and show accuracy of the proposed method when compared to the results from SAP2000 with energy criterion.

6. 3. Another Comparison of Proposed Method and Computer Analysis A 40-story reinforced concrete building is analyzed using SAP2000 software and optimum location of outrigger-belt truss is calculated. Results are compared to those obtained from the proposed method (Table 3). As in the previous example the comparison indicates relatively good accuracy for the proposed method, considering its simplicity and ease of use. Reasons for differences in results obtained from the proposed method and computer analysis based on energy criteria are: a) shear deformation is considered in the computer analysis while it is absent in the proposed model, b) the computer model considers the details whereas the proposed model is a simple cantilevered beam, c) in the analytic model, belt truss is considered to be rigid, whereas in the computer model it is not perfectly rigid.

TABLE 1. Optimum location of outrigger-belt truss system calculated via proposed method and Rahgozar and Sharifi's method

Type of Loading	Proposed Method	Rahgozar and Sharifi's Method
Uniformly distributed loading	0.441L	0.545L
Triangularly distributed loading	0.490L	0.571L
Concentrated load at top	0.667L	0.667L

TABLE 2. comparison of results obtained by proposed method, Rahgozar and Sharifi's method and computer analysis for a 30-story building

Type of Loading	Uniformly Distributed Loading	Triangularly Distributed Loading	Concentrated Load at Top
Proposed method	0.441L	0.490L	0.667L
Rahgozar and Sharifi's method	0.545L	0.571L	0.667L
SAP2000 (Energy Criterion)	0.400L	0.530L	0.700L
SAP2000 (Displacement Criterion)	0.467L	0.530L	0.700L

TABLE 3. Comparison of results obtained by displacement criteria and energy criteria for a 40-story building

Type of Loading	Proposed Method	Rahgozar and Sharifi's Method	SAP2000 (Energy Criteria)	SAP2000 (Displacement Criteria)
Uniformly distributed loading	0.441L	0.545L	0.400L	0.500L
Triangularly distributed loading	0.49L	0.571L	0.530L	0.5500L
Concentrated load at top	0.667L	0.667L	0.700L	0.700L

7. CONCLUSION

In this paper, energy criterion was used for obtaining optimum location of outrigger-belt truss along the height of a tall building structure. For this purpose, the combined system of framed tube, shear core and outrigger-belt truss was modeled using continuum approach. Effect of outrigger-belt truss and shear core on framed tube system was modeled using a rotational spring placed at outrigger-belt truss location. The method of finding the optimum location of equivalent spring is based on setting to zero the first derivative of energy equation with respect to spring position as measured from structure's base. Optimum location of outrigger-belt truss system for concentrated load at top of the structure, uniformly and triangularly distributed loadings along height of the structure were calculated respectively as 0.667, 0.441 and 0.490 of structure's height as measured from the base. The proposed method is simple and efficient; it can be useful in preliminary stages of the design process in which a large number of alternatives need to be tried quickly and accurately.

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Strain Energy

چکیده

در این مقاله روشی برای تعیین محل بهینه سیستم مهار بازویی و کمربند خرپایی بر اساس ماکزیمم کردن انرژی کرنشی سیستم مهار بازویی و کمربند خرپایی ارائه شده است. سازه ساختمان بلند با سیستم ترکیبی قاب محیطی، هسته مرکزی، مهار بازویی و کمربند خرپایی با استفاده از روش پیوسته مدل شده‌اند. در این روش سیستم قاب محیطی به یک تیر طره با مقطع قوطی مدل شده است. اثر سیستم مهار بازویی، کمربند خرپایی و هسته مرکزی بر روی پاسخ قاب محیطی در برابر بارهای جانبی به صورت فنر پیچشی در محل قرارگیری مهار بازویی و کمربند خرپایی در نظر گرفته شده است. محل بهینه این فنر با ماکزیمم شدن انرژی جذب شده توسط فنر بدست می‌آید. بدین منظور در ابتدا مشتق معادله انرژی نسبت به محل قرارگیری سیستم مهار بازویی و کمربند خرپایی از پای سازه مساوی صفر قرار داده می‌شود. محل بهینه سیستم مهار بازویی و کمربند خرپایی برای سه نوع بارگذاری یعنی برای بارگذاری گسترده یکنواخت و مثلثی در ارتفاع سازه و بار متمرکز در بالای سازه محاسبه شده است. دقت روش پیشنهادی با استفاده از چندین مثال عددی بررسی شده است. نتایج بدست آمده بیانگر دقت قابل قبول روش پیشنهادی می‌باشد.

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