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HOW TO REDUCE DRIFT OF BUILDINGS

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1. Introduction

There are three important items to be considered in steel structural design. These are:

1. *Details*
2. *Deflection*
3. *Stress and Strength*

A steel structure is built of ready-made steel members which are jointed with weld or bolts at the building site. Mechanical properties of a steel structure, such as strength and deformation capacity, shall be determined by the quality of members and also by the design of connection, balance, continuity and integrity. Therefore, the first item, ***Details***, is definitely the most important. But this is not the main subject of this paper.

Although the third item, *Stress and Strength* of structures, is also important, this will not become a serious problem because structural engineers usually don't fail to check these points in structural design. When the stress-over of certain members is discovered at the stage of design, the design can be changed simply by replacing those members with larger ones. This procedure can be performed easily with computer or hand calculation.

This paper treats the second item, *Deflection* of structures, as its main subject. It especially gives careful consideration to "Drift problem", the horizontal displacement of high-rise buildings induced by seismic or wind force. Drift problem is one of the most serious issues in high-rise building design, relating to the dynamic characteristics of the building during earthquakes and the uneasiness for residents during strong winds.

To obtain a displacement, Practical calculation method has been proposed, but in general Matrix method using computers has been used frequently. Actually, Practical calculation method can not be applied for buildings with complicated configurations.

Computers have the advantage of high-speed accurate calculations, but they also have the weak point of invisible calculation process. Particularly Drift, horizontal deflection of the top of a structure, shall be caused by the accumulated deformation of each member, such as a column, beam, brace and shear wall. Therefore, when we want to control the quantity of displacement by changing its design, we can not figure out which member of the structure should be changed, only from one result of computer calculation.

Technical intuitions based on past design experiences have played a principal role in structural design. Assuming that structural design is the optimization problem of multi-variables, "Trial and Error" can be regarded as the process to get the solution of a partial differential equation. Skilled design engineer have tried to figure out differential coefficients by repeating "Trial and Error", and they have tried to find out the right direction to its optimum solution. Technical intuitions have been obtained in this way, but they have been stored personally and they are difficult to be handed down to young engineers.

This paper aims at proposing a new logical design method on deformation, not depending on experiences and technical intuitions. So far the computer calculation of deformation has been performed in a black box. This paper recommends a new see-through box instead of this black box and suggests the way to complete excellent design with computers.

Although this method has different procedures, it can be regarded as a kind of Design Sensitively Analysis which is newly used for Structural Analysis Programs.

2. The change of displacement caused by changing section of members

2.1 Unit Load Method for Calculating the Displacement of Structures

When we perform structural analysis with computers, we generally use Matrix method which defines the displacement of each node as the unknown. In this case, the displacements of a structure are printed out automatically and we can check them easily.

On the other hand, the displacement of a structure shall be caused by the accumulation of each member's deformation as mentioned before, The computer output can not indicate which member's deformation has a large share in its displacement.

I would like to mention Unit Load Method for calculating displacements derived from the principles of Virtual work. Any structural engineer has learned this method at least once. Now, I propose a new analysis method on structural deformation using Unit Load Method.

According to References [2], the process of this method are as follows.

"The procedure for calculation a displacement by means of the unit-load method using Eq.1 may be summarized as follow : (1) determine the stress resultants N_L,M_L, and V_L in the structure caused by the actual loads : (2) place a unit load on the structure corresponding to the displacement D that is to be found : (3) determine the stress resultants N_U,M_U, and V_U caused by the unit load : (4) form the terms shown in Eq.1 and integrate each term for the entire structure : and (5) sum the results to obtain the displacement D."

$$D = \int \frac{N_U N_L}{EA} dx + \int \frac{M_U M_L}{EI} dx + \int \frac{\alpha V_U V_L}{GA} dx \qquad \text{Eq. 1}$$

Additionally, Prof. S.P.Timoshenko described the validity efficiency of this method as follows.

"The unit-load method can be used not only for beams, trusses, and other simple kinds of structures, but also for very complicated structures having many members. Furthermore, the unit-load method is suitable for finding all types of displacements, including the deflection of a point in the structure, the rotation of the axis of a member, the relative displacement between two points, and others. Theoretically, it may be used for either statically determinate or indeterminate structures, although for practical purposes the method is limited to determinate structures because its use requires that the stress resultants be known throughout the structure."

For these reasons, this method has been used only for hand calculation exercises at universities. In practical design, computers usually calculate structural deformation. There are very few engineers who take the trouble to calculate it by themselves using this method.
Today, Stress resultants of statically indeterminate structures can be obtained by computers. Unit load method has the advantage that it can analyze the source of displacement of certain point of a structure.
Therefore, this method can be practically used not only for statically determinate structures, but also for any type of structures.

2.2 Application to Statically Determinate Structures

As the simplest model, series springs are shown in Fig. 1.

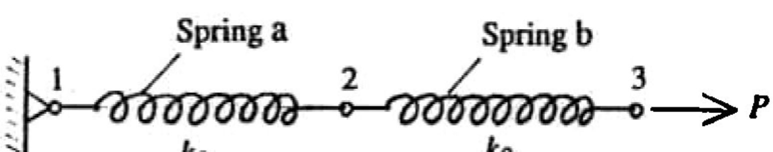


Fig. 1 Simple Statically Determinate Structure

Spring a,b are assumed to have the same spring constant k_0 ($= EA_0 / l_0$) : It is apparent that the axial forces of spring a, b can be represented by P : $N_{La} = N_{Lb} = P$. When a unit load is applied to point 3, the axial forces are expressed as, $N_{Ua} = N_{Ub} = 1$.

From Eq.1 of Unit load method, the displacement of point 3, defined as D_3, can be written as

$$D_3 = \int_{l_0} \frac{1\,P}{EA_0} dx + \int_{l_0} \frac{1\,P}{EA_0} dx$$

$$= \frac{Pl_0}{EA_0} + \frac{Pl_0}{EA_0} = \frac{P}{k_0} + \frac{P}{k_0} \qquad \text{Eq. 2}$$

By setting $d_a = P / k_0$, $d_b = P / k_0$, this equation becomes

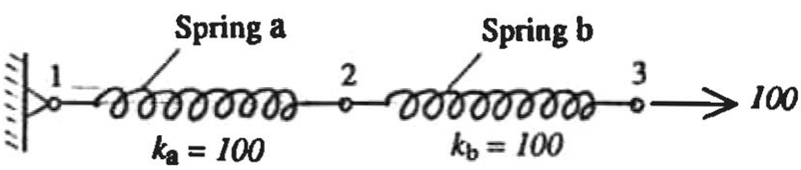
$$D_3 = d_a + d_b \qquad \text{Eq. 3}$$

We can think of d_a, d_b as constituents of D_3.

Then, I consider a modified case in which spring constants of spring a, b are multiplied by α_a, α_b respectively.

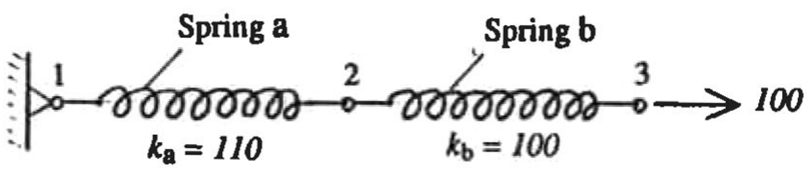
The displacement of point 3, defined as D_3', can be similarly obtained from Eq.2.

$$D_3' = \frac{P}{\alpha_a k_0} + \frac{P}{\alpha_b k_0} = \frac{d_a}{\alpha_a} + \frac{d_b}{\alpha_b} \qquad \text{Eq. 4}$$



$d_a = 1$ $d_b = 1$ $D_3 = 1 + 1 = 2$

Fig. 2.a Original Structure



$d_a = 1/1.1$ $d_b = 1$ $D'_3 = 1/1.1 + 1 = 1.909$

Fig. 2.b Modified Structure *Correct.*

This model is a statically determinate structure. Even if spring constants are changed, the stress resultants of them shall stay unchanged. Therefore the result of this calculation is a right solution as shown in Fig.2. Fig.2.a shows the original structure and Fig.2.b shows the modified structure in which left spring constant was multiplied by 1.1.

2.3 Application to Statically Indeterminate Structures

As the simplest model of a statically indeterminate structure, two parallel springs are shown in Fig.3.

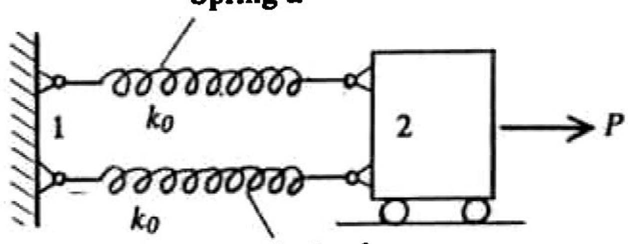


Fig. 3 Simple Statically Indeterminate Structure

D_2 can be expressed as $P/2k_0$ from basic technical knowledge. I figure out D_2 by means of the same method of statically determinate structures.

The axial forces of spring a, b caused by P can be represented by $P/2$, $N_{La} = N_{Lb} = P/2$. When a unit load is applied to point 2, the axial forces are expressed as, $N_{Ua} = N_{Ub} = 1/2$. D_2 can be obtained with these values using Eq.1

$$D_2 = \int_{l_0} \frac{\frac{1}{2}\frac{P}{2}}{EA_0}dx + \int_{l_0} \frac{\frac{1}{2}\frac{P}{2}}{EA_0}dx = \frac{P\,l_0}{4EA_0} + \frac{P\,l_0}{4EA_0} \qquad \text{Eq. 5}$$

By putting, $k_0 = EA_0 / l_0$

$$D_2 = \frac{P}{4k_0} + \frac{P}{4k_0} = \frac{P}{2k_0} \qquad \text{Eq. 6}$$

By setting $d_a = P / 4k_0$, $d_b = P / 4k_0$, this equation becomes

$$D_2 = d_a + d_b \qquad \text{Eq. 7}$$

We can think of d_a, d_b as constituents of D_2.

Then, I consider a modified case in which spring constants of spring a, b are multiplied by α_a, α_b respectively. The displacement of point 2, defined as D_2', can be obtained from basic technical knowledge.

$$D_2' = \frac{P}{(\alpha_a + \alpha_b)\,k_0} \qquad \text{Eq. 8}$$

According to Eq.4, assuming that the quantity of each spring's deformation changes in proportion to the change of each spring constant respectively, I propose a new simplified calculation method. A new equation can be obtained from Eq.7, by dividing d_a by α_a and dividing d_b by α_b and adding both of them:

$$D_2'' = \frac{d_a}{\alpha_a} + \frac{d_b}{\alpha_b} \qquad \text{Eq. 9}$$

I would like to check the change of D_2' corresponding to the change of k_a, k_b, using Differential and Integral calculus. $D_2' = P / (k_a + k_b)$ can be considered as the function with two variables k_a, k_b. From Taylor's theorem, D_2' can be approximated by first-degree equations as follows:

$$D_2''' = D_2 - \frac{P}{(k_a + k_b)^2}(\alpha_a - 1)\,k_a - \frac{P}{(k_a + k_b)^2}(\alpha_b - 1)\,k_b \qquad \text{Eq. 10}$$

Here I try to compare Eq.8 with Eq.9, Eq.10 from the results of real calculations.
By putting $k_a = k_b = 100$ and $P = 100$, we obtain $D_2 = 0.5$ in which $d_1 = d_2 = 0.25$.
Based on these values, by setting $\alpha_a = 1.0, 1.1, 1.2$ and $\alpha_b = 1.0, 1.1$, D_2' can be compared with D_2'', D_2''' as shown in Table 1.

Table 1 Comparison of Displacement D_2

Case	α_a	α_b	D'_2	$d_a/\alpha_a + d_b/\alpha_b = D''_2$	$(D''-D')/D'$	D'''_2	$(D'''-D')/D'$
1	1.0	1.0	0.500	0.250 + 0.250 = 0.500	-	0.500	-
2	1.1	1.0	0.476	0.227 + 0.250 = 0.477	0.2%	0.475	0.2%
3	1.2	1.0	0.454	0.208 + 0.250 = 0.458	0.9%	0.450	0.9%
4	1.1	1.1	0.454	0.227 + 0.227 = 0.454	0%	0.450	0.9%
5	1.2	1.1	0.435	0.208 + 0.227 = 0.435	0%	0.425	2.3%

D_2' is a right solution and D_2'' is a newly proposed approximate value. Although the spring constant has been changed 10-20%, the errors of D_2'' are quite small such as 0.2, 0.9, 0, 0%. The approximate values of Taylor theorem, D_2''', including an error 2.3% are not reasonable compared with D_2''. Eq.9 is ascertained to be effective from these simple calculations and D_2'' could be useful for its simple calculation.

According to these results, I propose quite a daring assumption for structural deformation as follows.

"The quantity of each member's deformation which causes the displacement of certain point of a structure changes in proportion to the change of its member's stiffness, and this quantity is not affected by the change of any other member's stiffness."

This assumption is perfectly right for statically determinate structures as shown in Fig.2. If there are no big changes in stress distribution, this assumption is almost right for statically indeterminate structures as indicated in Table 1.

3. Constituents of drift of the top of a building caused by lateral force

3.1 A New Calculation Method

Fig.4.a indicates the stress resultants of a building caused by design lateral load. Fig.4.b indicates the stress resultants of the same building when Unit load is applied to the top of the building. In these figures, i means the sequence number of each member and l_i, w_i mean the length and weight of member i.

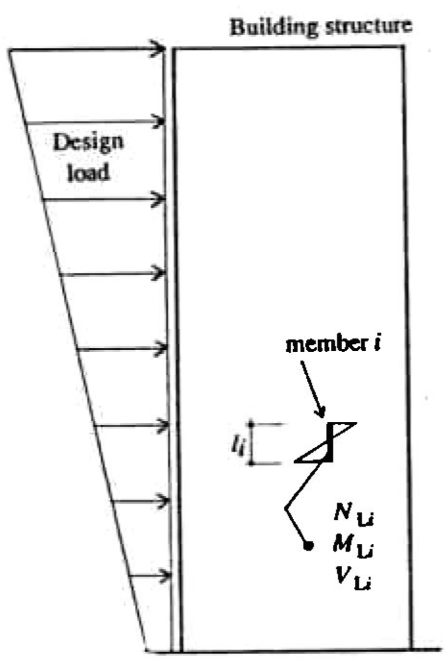


Fig. 4.a Stress Resultants Caused by Design Load

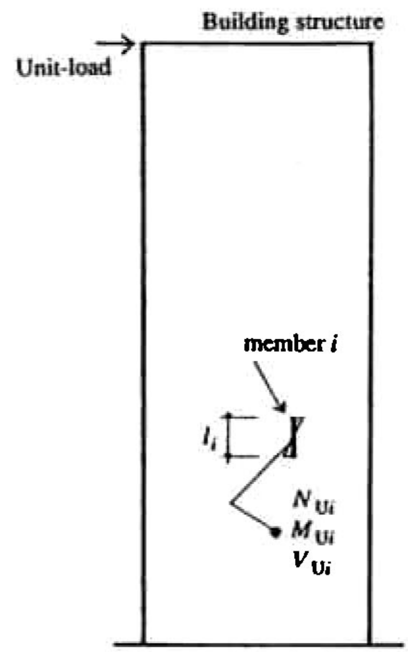


Fig. 4.b Stress Resultants Caused by Unit Load

By using the stress resultants of Fig.4.a, and Fig.4.b, and integrating Eq.1, the lateral displacement of the top of this building can be expressed as

$$D_{top} = \sum_{i=1}^{m} d_i \qquad \text{Eq. 11}$$

where

$$d_i = \frac{N_{Ui} N_{Li}}{EA_i} l_i + \int_{l_i} \frac{M_{Ui} M_{Li}}{EI_i} dx + \frac{\alpha V_{Ui} V_{Li}}{GA_i} l_i \qquad \text{Eq. 12}$$

Total weight of the structure can be given as

$$W_{total} = \sum_{i=1}^{m} w_i \qquad \text{Eq. 13}$$

The second term of Eq.12 can be easily obtained from Fig.5 as follows.

$$\int_{l} \frac{M_U M_L}{EI} dx = \frac{l}{6EI} \left(M_{Ua} (2M_{La} + M_{Lb}) + M_{Ub} (M_{La} + 2M_{Lb}) \right) \qquad \text{Eq. 14}$$

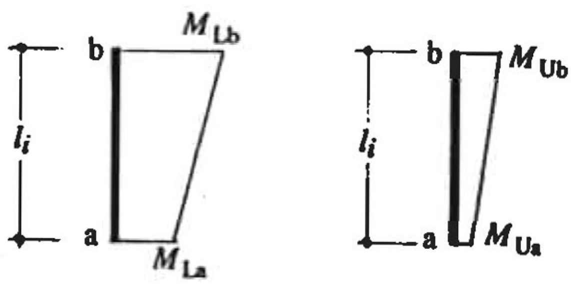


Fig. 5 Moment Distribution

3.2 Example

As a simple structure, a two-story steel frame is shown in Fig.6. Stress resultants caused by design load are schematically indicated in Fig.7.a, and stress resultants caused by Unit load are also indicated in Fig.7.b.

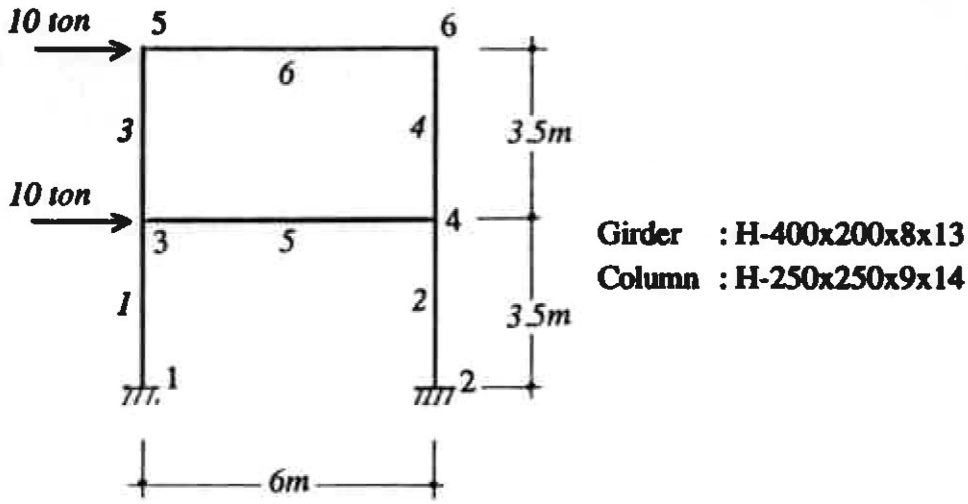


Fig. 6 Simple Frame

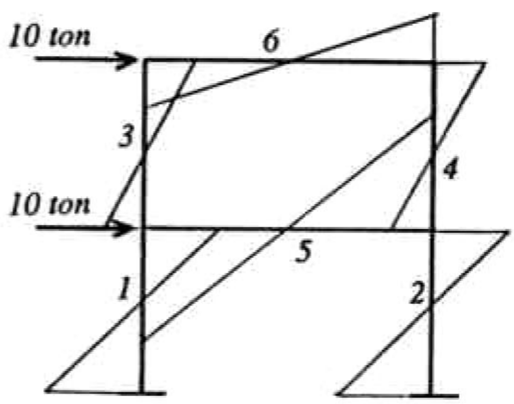


Fig. 7.a Stress Resultants Caused by Design Load

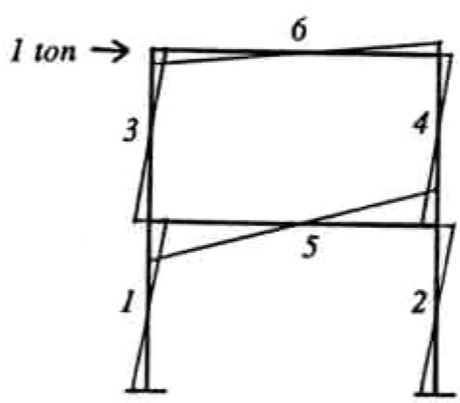


Fig. 7.b Stress Resultants Caused by Unit Load

The results of calculation of Eq.11 using stress distribution of Fig.7.a, 7.b are indicated in Table 2. The weight of each member is also indicated.

Table 2 Constituents of the Displacement of Point 5

i	d_{Ni} (cm)	d_{Mi}(cm)	d_{Vi} (cm)	d_i(cm)	w_i(ton)
1	0.016 (.33%)	0.905 (18.84%)	0.096 (2.00%)	1.017	0.2472
2	0.016 (.33%)	0.905 (18.84%)	0.096 (2.00%)	1.017	0.2472
3	0.002 (.04%)	0.420 (8.74%)	0.048 (1.00%)	0.470	0.2472
4	0.002 (.04%)	0.420 (8.74%)	0.048 (1.00%)	0.470	0.2472
5	0. (.00%)	1.317 (27.44%)	0.082 (1.70%)	1.399	0.3858
6	0. (.00%)	0.405 (8.43%)	0.025 (0.52%)	0.430	0.3858
Total				*4.803cm*	*1.7606ton*

We can derive from Table 2 which member's deformation has a large share in the displacement of point 5.

In Table 2

$$D_5 = \sum_{i=1}^{m} d_i = 4.803 \text{ cm}$$

Main constituents of D_5 can be picked up as follows.

$d_{M1} = d_{M2} = 0.905$ cm : the columns of 1st story
$d_{M3} = d_{M4} = 0.420$ cm : the columns of 2nd story
$d_{M5} = 1.317$ cm : the 2nd floor girder
$d_{M6} = 0.405$ cm : the roof girder

3.3 Practical application to big buildings

The example considered in 3.2 is a small-scale structure. We can easily check and decompose each member's deformation to examine the source of the displacement of the top of a building. In practical design, generally a building has more than ten thousand members. Besides, the decomposition of each member's deformation shall significantly increase the number of data.

Consequently, The number shall become so great that we can hardly grasp all of them. Spread Sheet Programs for personal computers such as *Excel* and *Wings*, will be quite useful to analyze these data. For example, they can sum up the deformations of columns, beams, braces and shear walls, separately. They can also sum up the deformations of all members belonging to a certain floor. They can also show the ratio of these constituents in a circle graph.

4. How to change section of members

4.1 The way to minimize the displacement without changing total weight

The displacement of the top of a building can be expressed as

$$D_{top} = \sum_{i=1}^{m} d_i \qquad \text{Eq. 15}$$

where d_i = the deformation of member i

Total weight of steel can be expressed as

$$W_{total} = \sum_{i=1}^{m} w_i \qquad \text{Eq. 16}$$

where w_i = the weight of member i

On the assumption that section of members can be changed only by controlling the thickness of the steel plate without changing its type of figure, the Area and Moment Inertia and Weight of member i, A_i, I_i, w_i, shall be changed in proportion to the coefficient α_i which controls the thickness of the plate.

According to 2.3, the deformation of changed member i can be written as d_i / α_i

Therefore, the displacement of the top of the changed building is expressed as

$$D'_{top} = \sum_{i=1}^{m} \frac{d_i}{\alpha_i} \qquad \text{Eq. 17}$$

From the assumption, total weight of steel is constant. Therefore this is given by

$$W_{total} = W'_{total} = \sum_{i=1}^{m} \alpha_i w_i \qquad \text{Eq. 18}$$

The problem to be solved here is finding the minimum of Eq.17 under the subsidiary condition Eq.18.

By applying Lagrange multiplier λ, Eq.17 can be rewritten as

$$D'_{top} = \sum_{i=1}^{m} \frac{d_i}{\alpha_i} + \lambda \left(\sum_{i=1}^{m} (\alpha_i w_i) - W_{total} \right) \qquad \text{Eq. 19}$$

By partially differentiating Eq.19 by α_i (i = 1,2,.... m) and λ, and then setting these equations to be equal zero, we can find the values of α_i (i = 1,2,.... m) and λ which minimize D'_{top}. These equations become

$$\frac{\partial D'_{top}}{\partial \alpha_i} = -\frac{d_i}{\alpha_i^2} + \lambda w_i = 0 \qquad (i = 1, 2, \ldots m) \qquad \text{Eq. 20}$$

$$\frac{\partial D'_{top}}{\partial \lambda} = \sum_{i=1}^{m} (\alpha_i w_i) - W_{total} = 0 \qquad \text{Eq. 21}$$

From Eq.20, α_i can be written as

$$\alpha_i = \sqrt{\frac{d_i}{\lambda\, w_i}} \qquad (i = 1, 2, \ldots m) \qquad \text{Eq. 22}$$

By substituting Eq.22 into Eq.21, consequently we obtain the weight of changed member i as follows

$$w'_i = \alpha_i w_i = \frac{\sqrt{d_i\, w_i}}{\sum_{j=1}^{m} \sqrt{d_j\, w_j}} W_{total} \qquad (i = 1, 2, \ldots m) \qquad \text{Eq. 23}$$

where the solutions of this problem α_i (i = 1,2,.... m), λ can be easily obtained.

In conclusion, the weight of member i whose section was changed to minimize the displacement of the top, can be obtained by allocating total weight of steel in proportion to the square root of the product of d_i and w_i. This simple formula could be understood intuitively and helpful to structural designers.

4.2 Example 1 A Statically Determinate Structure

A truss structure as an example of statically determinate structures is shown in Fig.8

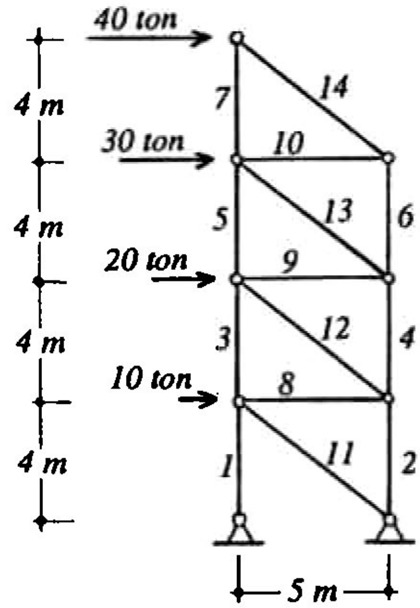


Fig. 8 Truss Structure

The number in this figure means the sequence number of each member. Member 1 through 7 are columns. Member 8 through 10 are girders. Member 11 through 14 are braces.

I performed the new calculation method of 4.1 for this truss structure. These results are listed on the Table 3. Fig.9 shows the sectional area of each member and the displacement of the top in the original design and in the changed design comparatively. From Fig.9, we can find these changes in sectional area reduce the displacement of the top from 7.512 to 6.375 cm. We also find all members with changed section area are well balanced and reasonably located.

4.3 Example 2 A Statically Indeterminate Structure

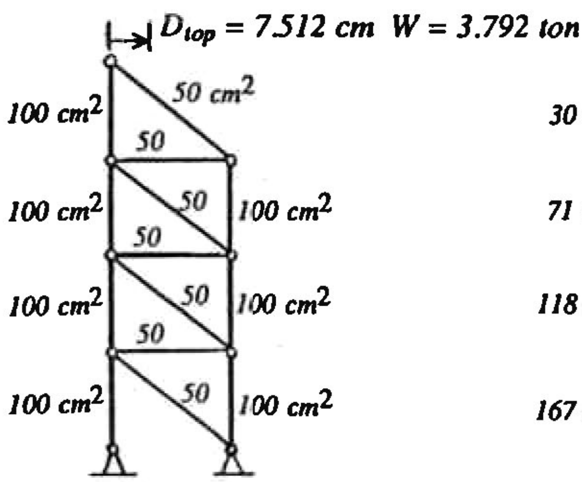
As an example of statically indeterminate structures, the two-story steel frame in Fig.6 is used again.

In accordance with the process of 4.1, the original design and the changed design are comparatively shown in Fig.10. This example is a statically indeterminate structure. Therefore, this result is obtained by performing the iteration twice.

By determining each member's sectional property reasonably without changing total weight of steel, we find the displacement of the top is reduced from 4.80 to 4.49cm.

Table 3 Calculation Process for Truss Structure

	Original Design						Changed Design	
i	$A_i(cm^2)$	$d_i(cm)$	$w_i(ton)$	$\sqrt{d_i w_i}$	$w'_i(ton)$	α_i	$A'_i(cm^2)$	$d'_i(cm)$
1	100	1.462	.314	.678	.523	1.665	166.5	.879
2	100	0.731	.314	.479	.340	1.177	117.7	.621
3	100	0.731	.314	.479	.340	1.177	117.7	.621
4	100	0.268	.314	.290	.224	0.713	71.3	.376
5	100	0.268	.314	.290	.224	0.713	71.3	.376
6	100	0.049	.314	.124	.096	0.304	30.4	.161
7	100	0.049	.314	.124	.096	0.304	30.4	.161
8	50	0.429	.196	.290	.224	1.140	57.0	.376
9	50	0.333	.196	.255	.197	1.005	50.3	.332
10	50	0.190	.196	.193	.149	0.760	38.0	.250
11	50	1.000	.251	.501	.387	1.539	76.9	.650
12	50	0.900	.251	.475	.367	1.460	73.0	.617
13	50	0.700	.251	.419	.323	1.287	64.4	.544
14	50	0.400	.251	.317	.245	0.973	48.7	.411
Total		7.512	3.792	4.914	3.792			6.375



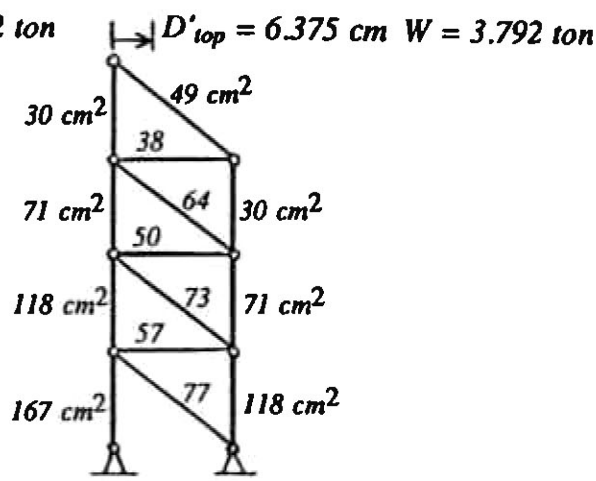


Fig. 9 Sectional Area and D_{top} of Truss Structure

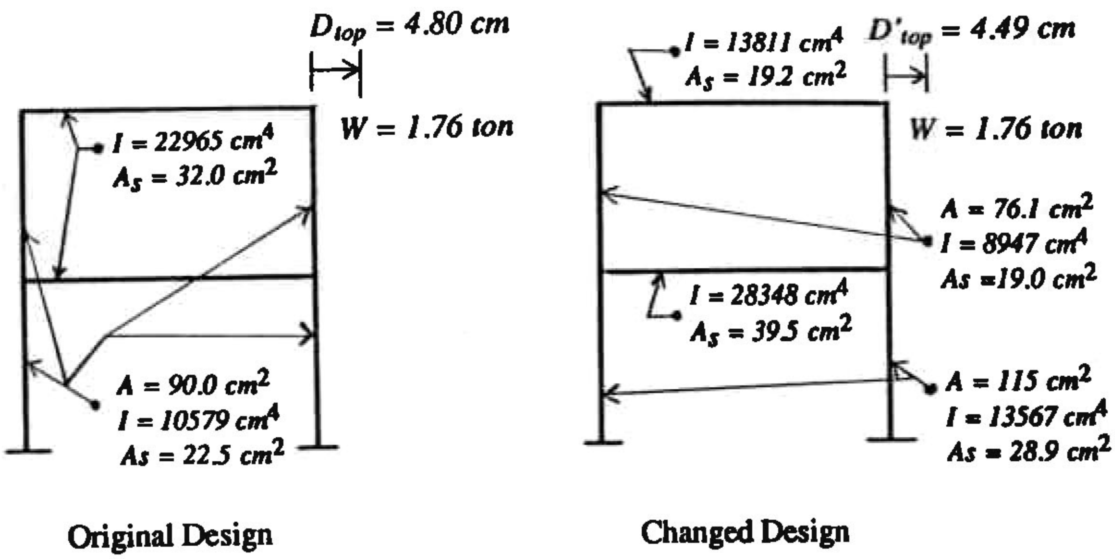


Fig. 10 Sectional Properties and D_{top} of Steel Frame

4.4 *The Way to Minimize Total Weight with Setting the Displacement to Design Value*

According to 4.1, D_{design} and W'_{total} are expressed as

$$D_{design} = \sum_{i=1}^{m} \frac{d_i}{\alpha_i} \qquad \text{Eq. 24}$$

Where D_{design} means the prescribed design value.

$$W'_{total} = \sum_{i=1}^{m} \alpha_i w_i \qquad \text{Eq. 25}$$

By applying Lagrange multiplier λ, Eq.24 can be rewritten as

$$W'_{total} = \sum_{i=1}^{m} (\alpha_i w_i) + \lambda \left(\sum_{i=1}^{m} \frac{d_i}{\alpha_i} - D_{design} \right) \qquad \text{Eq. 26}$$

By partially differentiating Eq.26 by α_i (i = 1,2,.... m), λ and then setting these equations to be zero, we can find the values of α_i (i = 1,2,.... m), λ which minimize W'_{total}. These equations become

$$\frac{\partial W'_{total}}{\partial \alpha_i} = w_i - \lambda \frac{d_i}{\alpha_i^2} = 0 \quad (i = 1, 2, \ldots m) \qquad \text{Eq. 27}$$

$$\frac{\partial W'_{total}}{\partial \lambda} = \sum_{i=1}^{m} \frac{d_i}{\alpha_i} - D_{design} = 0 \qquad \text{Eq. 28}$$

From Eq.27 α_i can be written as

$$\alpha_i = \sqrt{\frac{\lambda\, d_i}{w_i}} \quad (i = 1, 2, \ldots m) \qquad \text{Eq. 29}$$

By substituting Eq.29 into Eq.28, consequently we obtain the deformation of changed member i as follows

$$d'_i = \frac{d_i}{\alpha_i} = \frac{\sqrt{d_i\, w_i}}{\sum_{j=1}^{m} \sqrt{d_j\, w_j}} D_{design} \quad (i = 1, 2, \ldots m) \qquad \text{Eq. 30}$$

where the solutions of this problem α_i (i = 1,2,.... m), λ can be easily obtained. Additionally, the weight of changed member i , w_i can be expressed as

$$w'_i = \alpha_i w_i = \frac{\sqrt{d_i\, w_i} \sum_{j=1}^{m} \sqrt{d_j\, w_j}}{D_{design}} \quad (i = 1, 2, \ldots m) \qquad \text{Eq. 31}$$

5. Conclusion

Design is the product of human creativity. Even if Optimum Design Method is completed by computers, I think very few structural engineers will use computer design directly without any consideration. This paper considers mainly structural deformation and proposes the new method to improve structural design. In the mean time, unfortunately some engineers seem to treat the job of structural design using computers like playing computer games. I hope this paper could be helpful to make this job more sophisticated and intellectual.

In Computer age, technical intuitions are more difficult to be obtained as compared with Hand-calculation age. Therefore, some conservative engineers are afraid that frequent use of computers might be ruining the quality of engineers. Although I do not dare to oppose it, actually computer has been making great progress day by day and I think the important thing is how to use computers more efficiently. We should try to find out new methods which enhance engineers' technique and creativity by using computers. I believe that providing the process of computer calculation could be helpful, and I try to perform it in this paper.

This paper has developed a method on the assumption that the stiffness of each member is proportional to its weight. Next time, I would like to proceed with the method considering the change of each member's stiffness corresponding to the change of its depth and width. Furthermore, I will try to study deformation analysis which includes plastic deformation caused by large external loads.

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7. References

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