EARTHQUAKE RESPONSE ANALYSIS OF AN ONE-WAY LONG-SPAN TRUSS STRUCTURE WITH CONSIDERATION OF MEMBER BUCKLING

Hidemoto MUKAI* and Akira WADA**

* Graduate Student, Department of Environmental Engineering,
Tokyo Institute of Technology, Nagatsuta, Midori-ku, Yokohama, 227, Japan
** Dr. Eng., Professor, The Research Laboratory of Engineering Materials,
Tokyo Institute of Technology, Nagatsuta, Midori-ku, Yokohama, 227, Japan

This paper is a presentation of the structural design method by means of the SRSS method applied to every member and of the elasto-plastic earthquake response analysis method of space-truss structures. The analysis takes into account buckling in the relationship between the member's axial force and axial deformation. Furthermore, by applying the structural design method, double-layer cylindrical truss structure is elastically designed, and earthquake response analyses are carried out with several input levels. This paper indicates that the structural design method based on the SRSS method is effective, that the collapse of a double-layer cylindrical truss structure is subject to significant effects from buckling in the chord members in the span direction, and that in the case of a long-span truss structure it is necessary to consider the total vertical energy input due to the dead load of the structure.

1. INTRODUCTION

To ensure the safety of a long-span structure in Japan, it is necessary to correctly assess its behaviors not only under strong winds but also under earthquakes. Generally, in seismic design of a steel structure, the toughness of the frame is expected and the design is carried out assuming the plasticity of the structure during a big earthquake. However, if a similar concept is used in the design of a long-span truss structure, it is likely for some members of the structure to buckle due to the earthquake. The recent development of high performance computers, particularly super computers, has made it feasible to carry out elasto-plastic response analysis of full-sized structures, taking into account the elasto-plastic characteristics of every member, thereby indicating even the extent of buckling of an individual member.
In this paper, the SRSS method is used to examine the axial forces of truss members. Followed by earthquake response analyses of an elastically designed, double-layer cylindrical truss structure with several input levels, in order to assess this elastic design method as well as evaluate it by energy input.

2. ANALYTICAL METHOD

2.1 Analytical Assumptions

(1) All members are assumed to be truss elements, with pin connected ends. Deformation is taken into account only in the axial direction.
(2) Buckling is considered in the axial force – axial deformation relationship of an individual member, according to the method established by Shibata et al.[1], as shown in Fig.1.
(3) Mass is treated as a mass concentrating on a joint, and the force of inertia does not act in the middle portion of a member. In addition, coupled vibration between a member and the structure is negligible.

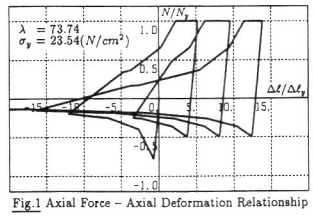

Fig.1 Axial Force – Axial Deformation Relationship

etc., the mass, which is 0.125 ton in the joints at four corners, 0.250 ton in other joints at the sides, and 0.500 ton in all other joints, is added on each of joints of the upper chord members.

4. ANALYTICAL RESULTS

4.1 Structural Design Results

Fig.3 shows the arrangement of the members designed according to a spectrum which modified the damping constant in the Umemura spectrum[3] to 0.02, with the horizontal earthquake intensity 0.35G and the up-and-down earthquake intensity 0.175G. Table 1 shows the sectional properties. Fig.4 shows the distributions of the maximum axial forces due to earthquake motion calculated by the SRSS method as well as the elastic earthquake response analysis covering the input earthquake motion 0.35G. Compared to the elastic earthquake response analysis, the SRSS method has a tendency for overestimation, but both distributions of the axial forces are similar.

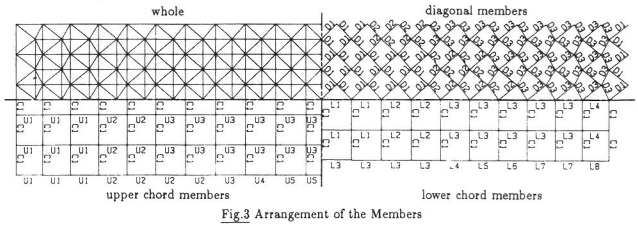

Fig.3 Arrangement of the Members

Table 1 Sectional Properties

kind of members	number	length (cm)	area (cm^2)	radius of gyration(cm)	slenderness ratio
upper chord members in the span direction	U1	997.2	68.5	11.0	90.54
	U2		87.4	12.3	81.12
	U3		112.4	14.1	70.96
	U4		148.7	14.0	71.53
	U5		196.2	13.8	72.23
lower chord members in the span direction	L1	977.3	68.5	11.0	88.73
	L2		87.4	12.3	79.51
	L3		112.4	14.1	69.54
	L4		148.7	14.0	70.10
	L5		196.2	13.8	70.79
	L6		231.2	13.7	71.25
	L7		261.6	15.5	63.03
	L8		291.9	17.3	56.48
chord members in the ridge direction	C1	1000.0	52.4	7.4	135.77
diagonal members	D1	808.5	40.4	6.5	124.27
	D2		46.0	7.4	109.27
	D3		57.3	9.2	87.76

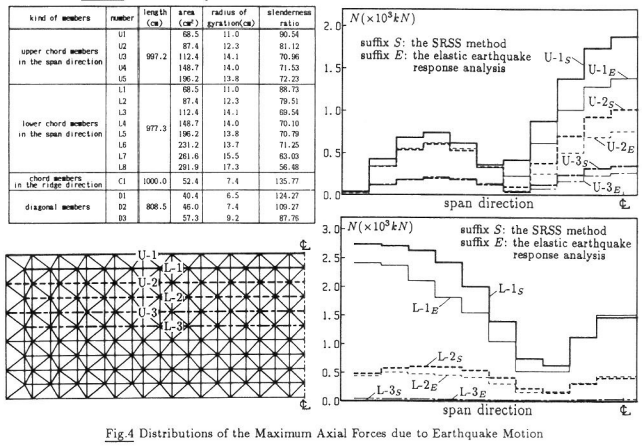

Fig.4 Distributions of the Maximum Axial Forces due to Earthquake Motion

2.2 Structural Design Method

Each of members is selected from the members provided in advance, so that the axial force of the member due to the dead load is within the range of allowable axial force for long-term loading. Also the axial force responding to the earthquake resistant design is within the range of allowable axial force for short-term loading. The latter axial force of the i member, N_i is derived by the SRSS method compatible with an individual member[2] shown in the equation (1).

$$N_i = N_i^S \pm \sqrt{\sum_{s=1}^{n} ({}_s\beta_d \cdot {}_sN_i^D \cdot {}_sS_D)^2} \qquad (1)$$

where N^S is an axial force due to the dead load; ${}_s\beta_d$ is a model participation factor in the direction of d; N^D is a response axial force; and S_D is a displacement response spectrum, where the suffix i represents the i member and the prefix s represents the degree of vibration mode.
In each of the directions X, Y and Z, method of selecting members is iteratively continued until no more change is required. Member with the greatest allowable axial force of the results obtained from the calculation for three directions respectively is selected for component.

2.3 Earthquake Response Analysis Method

Earthquake response analysis is carried out as described below, following static analysis by means of dead load. On the assumption that the current tangential stiffness of a structure, $[K(t)]$, is constant within the time step Δt, the vibration equation which covers increased response displacement is shown in the equation (2) and the response displacement is calculated by the linear acceleration method.

$$[M]\{\ddot{y}_{n+1}\} + [C]\{\dot{y}_{n+1}\} + [K(t_n)]\{\Delta y_n\} + \{F_n\} = -[M]\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \end{bmatrix}\begin{Bmatrix} \ddot{y}_{GX\,n+1} \\ \ddot{y}_{GY\,n+1} \\ \ddot{y}_{GZ\,n+1} \end{Bmatrix} + \{Q\} \qquad (2)$$

where $\{\Delta y_n\} = \{y_{n+1}\} - \{y_n\}$; $\{F\}$ is a initial stress vector; $\{Q\}$ is a load vector due to dead load; and the suffix n represents $t = t_n$.
The damping matrix is a type of proportional to stiffness, and the damping constant is 0.02. The current tangential stiffness matrix is obtained from an element stiffness matrix based on the theory with consideration of the effects of large displacement.

2.4 Input Earthquake Motion

The El Centro NS component is input in the Y direction for ten seconds, and then the free vibration is performed for five seconds. Response analyses are carried out for seven cases with the maximum acceleration of the input earthquake motion (input acceleration) setting at 150, 300, 400, 500, 600, 650, and 700 gals. The time interval for response calculation, Δt, is 0.001 second.

3. ANALYTICAL MODEL

Fig.2 shows An analytical model of the double-layer cylindrical truss structure. The structure is given the configuration: one grid approx. 10 × 10m, span B=200m, length L=50m, layer depth = 4m, center half-open angle $\phi = 30°$. In addition, the joints in the lower chord members located between a-b and c-d in Fig.2 are pin-supported. The mass of a member calculated with the specific gravity of steel assumed as 7.86, is allocated in both joints. And then, taking into account the finishing materials

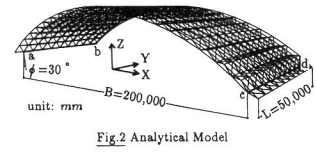

Fig.2 Analytical Model

2.4 Earthquake Response Analysis Results

The earthquake response analysis results indicate that all members are within the range of elasticity when the input accelerations are 150 gals and 300gals. Fig.5 shows the time histories of the average vertical displacement of the structure when the input accelerations are in the range of 400 to 700 gals. When members are within the range of elasticity, it is slightly vibrated around the average vertical displacement caused by the initial dead load, but as the number of chord members buckled in the span direction increase, it increase. Up to the input acceleration of 600 gals, rows with all non-buckled members in the span direction are in existence, that ensures the stresses re-distributing in that span direction and prevents the structure from collapsing. However, beyond 650 gals, no rows in the span direction which is composed by non-buckled members exist, that consequently prevents the inflow of stresses and the whole structure collapses.

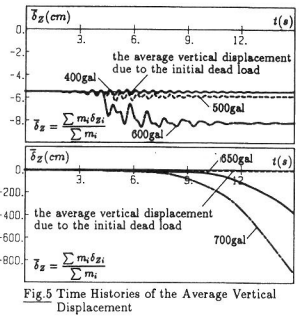

Fig.5 Time Histories of the Average Vertical Displacement

Fig.6 shows the relationship of total energy input in the direction of earthquake motion input (the Y direction) and that in the vertical direction (the Z direction). The total energy input is greater in the Y direction than in the Z direction, and the ratio of the increase in the Z direction to the increase in the Y direction is approximately equal within the range of elasticity. However, the structure come to a collapse with the increasing ratio, along with members being buckled one after another.

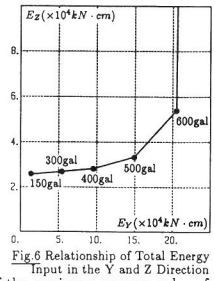

Fig.6 Relationship of Total Energy Input in the Y and Z Direction

5. CONCLUSIONS

The use of the super computer has made it feasible to conduct elasto-plastic earthquake response analysis of a space-frame truss structure taking into account the relationship between the axial force and axial deformation of the members, which correspondingly leads the author to the following conclusion regarding the proposed structure.
1) As the SRSS method uses the square root of sum of squares of the maximum response value of each individual vibration mode, there is a tendency to overestimate the response results, but the state of distributed axial forces responds well to the results of elastic earthquake response analysis. In addition, the results of elasto-plastic earthquake analysis assume the effectiveness of the proposed structural design method using the SRSS method.
2) The collapse of a double-layer cylindrical truss structure is attributable to the buckling of the chord members in the span direction.
3) With increasing damage to the structure, an increase in the total energy input in the vertical direction is noticeable with respect to the direction of a horizontal earthquake motion. Thus, in the case of a long-span truss structure, it is necessary to take into account the total energy input due to its dead load in a vertical direction.

6. REFERENCES

[1] Shibata,M. and Araki,H. : Elastic-plastic Analysis of a Braced Frame with Piecewise-linear Restoring-force Function of Brace (Part 1), Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan, pp.989-990, Aug. 1986 (in Japanese)
[2] Sugano,T., Kobayashi T. and Kondo K. : Seismic Design of a Long-span Space Structure, Proceedings of the Sessions Related to Seismic Engineering at Structures Congress '89, pp.368-377, May 1989
[3] Shibata,A. : New Aseismatic Structure Analysis, p.38, 1986 (in Japanese)

Reprinted from the Extended Abstracts
of the IV-ICCCBE '91 Conference, Tokyo.