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A FRACTURE CRITERION FOR TUBULAR BRACING MEMBERS AND ITS APPLICATION TO INELASTIC DYNAMIC ANALYSIS OF BRACED STEEL STRUCTURES

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SUMMARY

This paper presents a criterion to predict fracture of rectangular tubular bracing members. The criterion includes two parts: normalizing deformation cycles into standard cycles, and predicting the fracture life of the bracing members in terms of the standard cycles. The criterion is incorporated into DRAIN-2DM, a general purpose computer program for dynamic analysis of inelastic structures. The US-Japan Phase I test structure, a six-story steel structure with concentric bracing, is analyzed for the Miyagi-Ken-Oki earthquake. The analytical results with and without the criterion are compared with test results.

INTRODUCTION

Bracing members in concentrically braced structures are subjected to large cyclic deformations during a severe earthquake causing overall as well as local buckling. Some recently conducted full and small-scale tests (Refs. 1,2) and analyses (Refs 3,4) have shown that severe local buckling may result in premature fractures of bracing members designed according to the current practice. This may result in significant loss of lateral stiffness and large drifts in some stories leading to severe damage in beams and columns. In order to study the response of structures after fracture of some bracing members it is necessary to establish a criterion to predict fracture life of the bracing members. This paper presents an empirical criterion based on tests of bracing members of rectangular tubular sections. The procedure is as follows:

1. Normalize deformation history into standard cycles, N_s.
2. Compute fracture life of the member in terms of standard cycles, N_f.
3. When fracture life is exceeded the member is fractured.

NORMALIZATION OF DEFORMATION CYCLES

The deformation history of a bracing member represents the axial deformation varying with time or number of cycles. A cycle is defined herein as starting from a peak compression deformation to the next one. The cycle can be characterized by two parameters: amplitude (the tension deformation in the cycle) and deformation level (the initial deformation). As shown in Fig. 1 cycle 1-2 has an amplitude of Δ_y and cycle 2-3 has $2\Delta_y$, etc.. A standard cycle is defined as a cycle with an amplitude of Δ_y and zero deformation level. The following assumptions (illustrated in Fig. 1) are made in order to find equivalence between a general cycle and a number of the standard cycles:

1. The cycles whose amplitudes are less than Δ_y can be ignored.
2. The amplitudes are proportional, i.e., a cycle with an amplitude of $4\Delta_y$ is equivalent to 4 cycles with amplitudes of Δ_y.
3. Deformation level has no effect, i.e., a cycle starting at zero deformation is equivalent to the one starting at Δ_y.

Based on the assumptions the equivalent number of standard cycles can be determined as follows. For the simple cycles such as cycles 1-2, 2-3 in Fig. 1,

$$N_s = \frac{\Delta_t}{\Delta_y} \quad (1)$$

For the incremental cycles such as cycles 3-4 in Fig. 1:

$$N_s = \frac{\Sigma(\Delta_t - \Delta_c)}{\Delta_y} \quad (2)$$

where Δ_t=tension deformation, Δ_c=compression deformation of the cycles. With the above procedure a cyclic deformation history can be converted into a simple history consisting of a number of standard cycles as shown in Fig. 2. Points 1 - 4 in the deformation history can be found to be equivalent to the corresponding points 1 - 4 in the standard history.

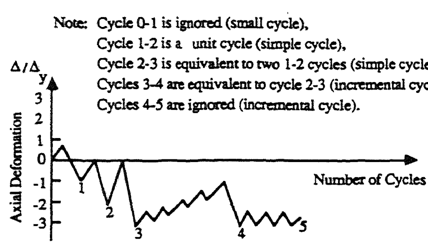

Figure 1 Typical Cycles In A Deformation History

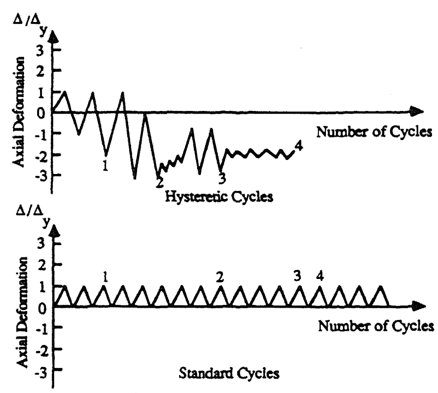

Figure 2 Equivalent Conversion Between Hysteretic Cycles And The Standard Cycyles

CRITERION TO PREDICT FRACTURE LIFE IN TERMS OF THE STANDARD CYCLES

Cyclic loading tests on bracing members of rectangular tubular sections made of A500 grade B steel were recently conducted at The University of Michigan (Refs. 5,6). The results show that the fracture life of the bracing members depends on slenderness ratio, width-depth ratio and width-thickness ratio of the compression flange of the sections. It can be expressed as (Ref. 4):

$$N_f = C_s \frac{(b/d)(KL/r)}{\left[(b-2t)/t\right]^2} \qquad KL/r > 60 \quad (3)$$

$$N_f = C_s \frac{(b/d)(60)}{\left[(b-2t)/t\right]^2} \qquad KL/r \le 60 \quad (4)$$

where C_s is a numerical constant of 262 obtained from the test results.

The above criterion is incorporated in the DRAIN-2DM program (Ref. 7). The program is used to compute the response of the US - Japan Phase I structure in the inelastic test due to the Miyagi-Ken-Oki accelerogram with the maximum acceleration scaled to 500 $cm/sec.^2$. The full-scale steel structure shown in Fig. 3 was designed to satisfy both the Uniform Building Code and the Japanese Seismic Design Code (Ref. 8)) and was tested at Building Research Institute of Japan using psuedo-dynamic method (Ref. 2). Modeling details are given in Ref.4.

Without Considering Fracture of Bracing Members The analytical floor responses match with the test results very well up to about 8.2 seconds, as shown in Fig. 4. At this instant both bracing members in the second story and the north one in the third story started cracking in the test and fractured shortly thereafter. Because the fracture is not considered in this analysis the discrepancies between the analytical and test results become significant after 9 seconds.

Considering Fracture of Bracing Members Some bracing members had undergone cyclic buckling during the moderate test (Ref. 2) which was performed before the inelastic test. As a result some of their fracture life was dissipated. Fracture life of the bracing members (in terms of standard cycles) is calculated by using Eqs.(3) and (4). Effective length factor K is assumed to be 0.7(Ref.4). The balance of the fracture life is shown under the column N_f' in Table 1.

Table 1. - Fracture Life of Bracing Members

Story & Side	Section Size	KL/r	b/d	(b-2t)/t	N_f	N_m'	N_f'
1 N:	6x6x1/2	64.1	1.0	10.0	168	0	168
S:					168	0	168
2 N:	6x6x1/4	60.0	1.0	22.0	33	8	25
S:					33	10	23
3 N:	6x6x1/4	60.0	1.0	22.0	33	8	25
S:					33	6	27
4 N:	5x5x1/4	63.0	1.0	18.0	51	1	50
S:					51	0	51
5 N:	5x5x3/16	62.0	1.0	24.7	27	3	24
S:					27	0	27
6 N:	4x4x3/16	79.0	1.0	19.3	56	0	56
S:					56	0	56

Table 2. - Cracks and Fractures of Bracing Members

Sequence	Analysis			Test		
	Member	Time	Condition	Member	Time	Condition
1	3S-N	9.7	Fracture	3S-N	8.2	Crack
2	2S-N	9.7	Fracture	2S-N	8.2	Crack
3	5S-N	9.8	Fracture	2S-S	10.8	Crack
4	2S-S	11.5	Fracture	(The test stopped shortly		
5	5S-S	15.2	Fracture	after 11 seconds)		
6	4S-N	16.6	Fracture			

The floor responses from the analysis and the test are compared in Fig. 5. A good agreement can be seen throughout the 11 second duration of the test. The north bracing member in second story cracked at 8.2 seconds in the test. In the analysis no member fractures until 9.7 seconds when the north bracing members in the second, third and fifth stories fracture almost simultaneously. Therefore, a slight discrepancy between the experimental and analytical responses can be noticed in Fig. 5 between 8.2 and 9.7 seconds. After 9.7 seconds the two response curves match very well. Fig. 6 shows analytical deformation histories of some bracing members. The timing of bracing fractures in both the test and the analysis are given in Table 2. Fractures of bracing members significantly reduce story shear transfer capacity and therefore, significantly reduce story shear forces. Due to much reduced lateral stiffness large drifts occur causing severe damage. The other stories move more or less as rigid bodies. Structural damage and deformed shape are shown in Fig. 7.

CONCLUSIONS

An empirical criterion is presented to predict bracing member fractures and is incorporated into the general purpose computer program DRAIN-2DM. It can be used to compute post brace-fracture response of inelastic structures during severe earthquakes. The analysis of the US-Japan test structure shows very good agreement with the test results. Although, the procedure developed herein is primarily for bracing members of rectangular tubular sections the methodology is generally applicable for other types of bracing members. It should be noted that this is a first attempt in this direction.

Brace fractures significantly reduce lateral stiffness and shear resistance in the stories where bracing members fracture. This may result in large lateral drifts and severe damage. The other stories move almost as rigid bodies due to their relatively large stiffness.

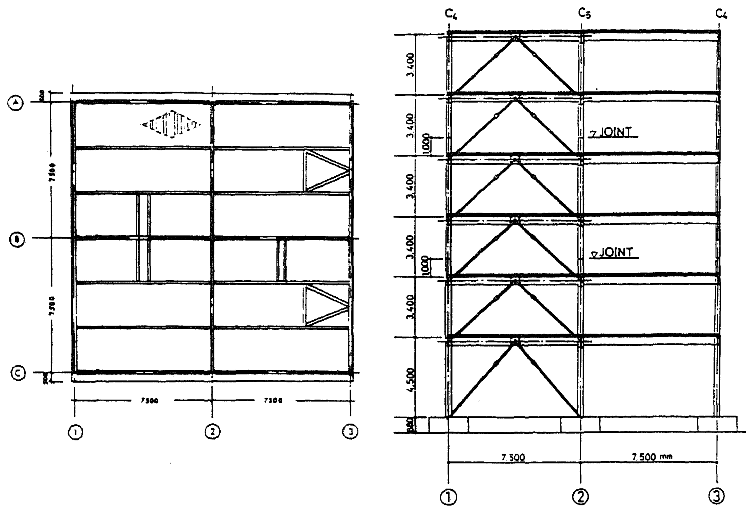

Figure 3 Floor Plan And Frame B Of The US-Japan Phase I Steel Test Structure

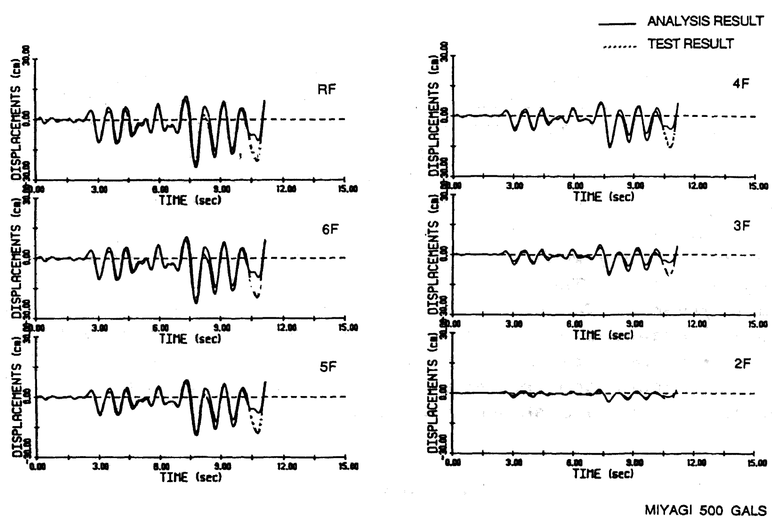

Figure 4 Analytical And Test Results Of Floor Responses - Brace Fractures Not Considered in Analysis

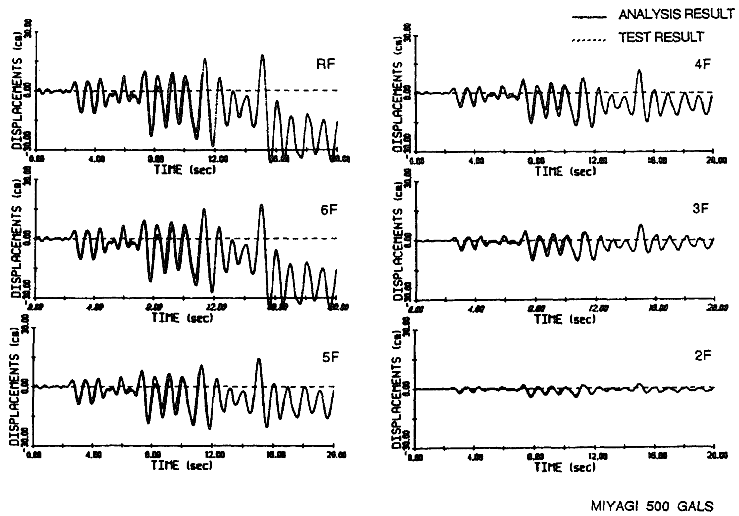

Figure 5 Analytical And Test Results Of Floor Response - Brace Fractures Considered in Analysis

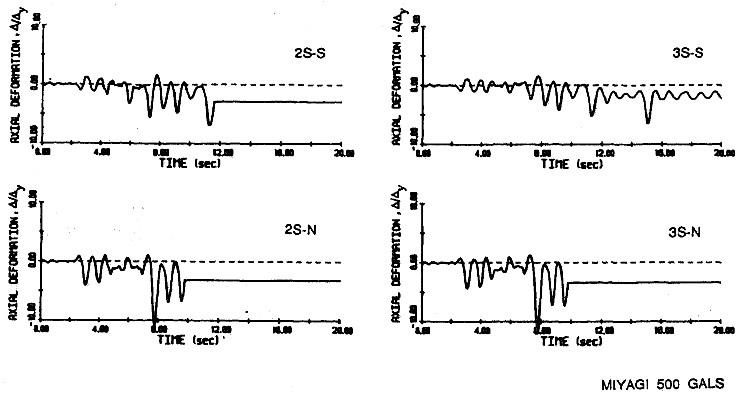

Figure 6 2nd And 3rd Story Bracing Member Deformation Histories

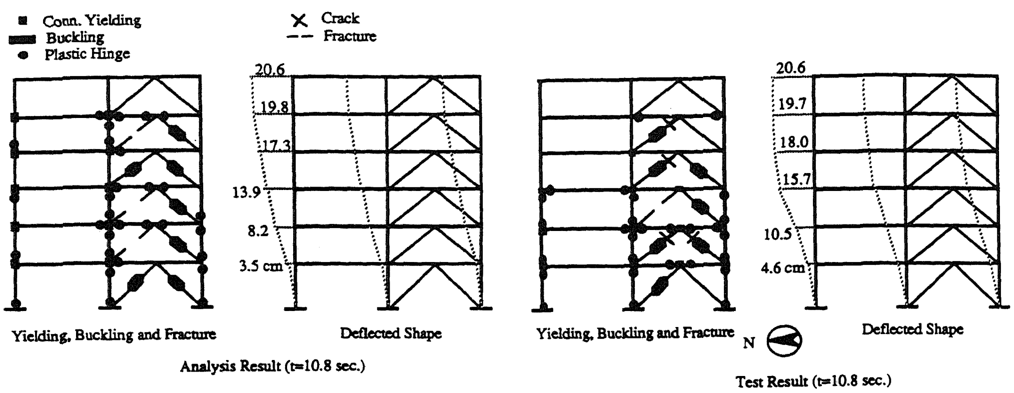

Figure 7 Yielding, Buckling, Facture And Deformed Shape
- Miyagi-Ken-Oki Earthquake(500 gals)

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