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CYCLIC ELASTO-PLASTIC BEHAVIOUR OF TUBULAR COLUMNS UNDER BI-DIRECTIONALLY APPLIED LOADS

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INTRODUCTION

The unprecedented damage to steel structures during the 1995 Hyogo-ken Nanbu Earthquake brought to light the complexity of earthquake excitation and response of structures. Although most seismic design codes assume independent action of the uni-directional design seismic motion, in reality, earthquake ground motion is random in nature, and has at least two simultaneous horizontal components causing response in oblique directions and biaxial bending in columns[1,2]. Hence, in-depth understanding of the inelastic load-deformation behaviour of steel columns under cyclic multi-directional load paths is obviously important in seeking enhanced resistance of structures to severe seismic excitation. This study investigated the effects of bi-directional load histories on the response of tubular steel columns widely used in the construction of elevated highways and building structures.

EXPERIMENTATION

Studies were conducted on four identical steel box columns, fabricated as thin-walled rectangular hollow steel columns of size B=150mm, D=100mm, t=4.22, length L=881mm and effective length (h)=846mm as shown in Fig. 1. The columns were tested as cantilever columns under constant axial load and each subjected to a different lateral load history using a newly developed multi-directional structure testing system. The lateral load histories investigated included cyclic loading in designated X-direction, Y-direction, biaxial-linear direction, and biaxial-rectangular direction. During testing, each column specimen was subjected to a constant axial load to simulate the weight of superstructure of magnitude $P=0.2P_y$ where P_y is the axial yield load, and lateral cyclic loads in the desired direction, of incremental displacement amplitudes, namely multiples of the predicted yield displacement δ_{y0} due to lateral load in the respective directions. For each displacement amplitude three cycle tests i.e. three cycles of gradual loading and unloading were conducted. Table 1 gives details of the test program. The yield lateral load (H_{y0}) and displacement at yield (δ_{y0}) in each of the respective X, Y directions were predicted from equations below, for the case of zero axial load.

$$H_{y0} = \sigma_{sy} I/(Z_t h) \quad (1)$$

$$\delta_{y0} = H_{y0} h^3/3EI \quad (2)$$

where I = sectional moment of inertia, Z_t = distance to extreme fibre from the centre of gravity, h = effective height of specimen, σ_{sy} = yield strength, and E_s = modulus of elasticity.

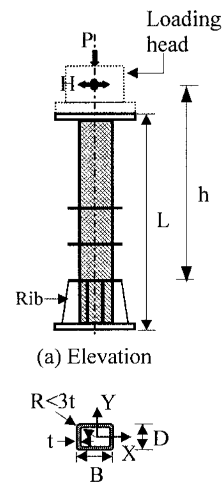
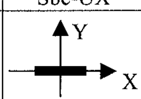
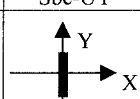
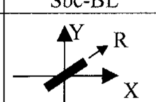
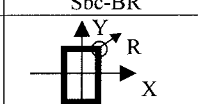
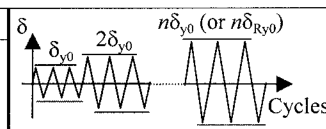


Figure 1 Typical test specimen

Table 1 Loading and cycling histories

Specimen	Sbc-UX	Sbc-UY	Sbc-BL	Sbc-BR	
Load path	 Uniaxial-X	 Uniaxial-Y	 Biaxial-Linear	 Biaxial-Rectangular	 Typical three-Cycle tests

Note: For the biaxial loading histories, the yield displacement (δ_{Ry0}) is defined as the resultant of yield displacements in the X and Y directions i.e. $\delta_{Ry0} = \sqrt{(\delta_{y0})^2_{x-axis} + (\delta_{y0})^2_{y-axis}}$

Material properties for the steel, determined from tensile tests on strips cut from the plates of steel box, are given in Table 2, where σ_{su}, ε_{sy} and ν_s stand for ultimate strength, yield strain and Poisson's ratio, respectively. Therefore, the plate slenderness parameter (R) for narrow plates is 0.53, while that for wider plates is 0.79.

Table 2 Steel material properties

σ_{su} (N/mm^2)	σ_{sy} (N/mm^2)	ε_{sy} (%)	E_s (KN/mm^2)	ν_s	Elongation (%)
446	373	0.177	211	0.272	41.0

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RESULTS AND DISCUSSIONS

Typical hysteretic response curves of the tested columns are presented in Figs. 2-4, which show response in X-direction. The arrow mark pinpoints the ultimate normalized horizontal load, and thus gives the ductility when extended to intersect the horizontal axis.

On observing Figs. 2-4, a reduction in strength and ductility of columns subjected to biaxial loading, when compared to column due to uniaxial loading, is promptly recognized. In the case of uniaxial loading, when the maximum stress is attained in two most stressed opposite plates (flange plates) it would seem that plastic flow occurs whereby additional stress is redistributed to the orthogonal plates (web plates). These orthogonal plates continue to resist load until their maximum stress level is attained. On the other hand, biaxial loading induces stresses simultaneously in all the four plates forming the box section converting them into flange plates. Hence column degradation is more severe and rapid. A further effect of biaxial loading is the more rapid reduction of column stiffness at each subsequent cycling amplitude. The degradation is more severe in the inelastic range, especially in the softening region beyond the ultimate load. It may be said that in the inelastic range, the plates forming the box section become inter-dependent in resisting the applied load through stress redistribution. Biaxial-rectangular loading history is noted to cause the most rapid softening degradation, perhaps due to the fact that it is of the longest path.

The rapidly degrading effects of biaxial interaction were also observed physically in the form of local buckling occurring in the portion just above the ribs. The column loaded in Biaxial-Rectangular direction (Sbc-BR) had the earliest visible buckling at $2\delta_{Ry0}$, followed by column Sbc-BL of Biaxial-Linear direction at $3\delta_{Ry0}$, column Sbc-UY of Uniaxial-Y direction at $3\delta_{y0}$ and finally column Sbc-UX of Uniaxial-X direction at $4\delta_{y0}$.

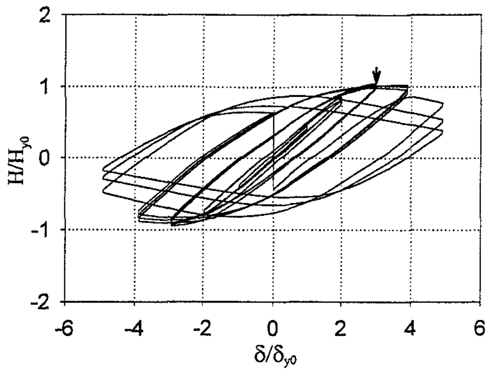

Figure 2 Normalized lateral load-displacement response in Uniaxial-X direction

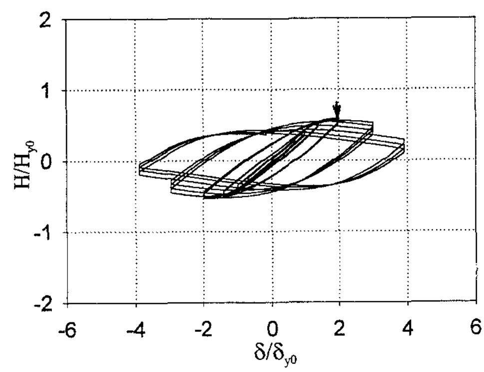

Figure 3 Normalized lateral load-displacement response in Biaxial-Linear direction (X-component)

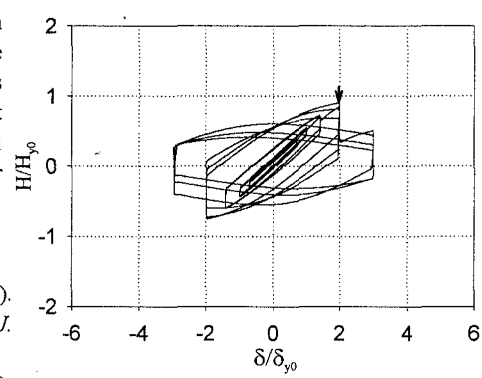

Figure 4 Normalized lateral load-displacement response in Biaxial-Rectangular direction (X-component)

CONCLUSIONS

In comparison with uniaxial displacement paths, biaxial displacement paths cause more extensive degradation of column stiffness, strength and ductility, in each of the two transverse directions considered separately. The most damaging such path is that of Biaxial-Rectangular direction. It is particularly noted that the severity of local buckling is more pronounced under biaxial loading especially for the case of the non-proportional rectangular loading.

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