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Effect of Severe Temperatures and Restraint on Instability and Buckling of Elliptical Steel Columns

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ABSTRACT

This paper presents the findings of an experimental research to investigate the performance of axially restrained elliptical hollow (EHS) steel columns subjected to severe hydrocarbon fire. The test programme involved 12 steel columns presenting 2 oval sections 200 × 100 × 8 mm and 300 × 150 × 8 mm and yielding 2 slenderness λ = 51 and 33. The 1800 mm columns were tested under loading ratios ranging between 0.2 and 0.6 of the ultimate strength determined using EC3 and under axial restraint degree ranging from 0 to 0.16. The obtained results of axial displacements, lateral displacements, measured restraint forces, and high temperatures are presented in the paper. It was found that introducing restraint to the columns with elliptical section produces high restraint forces which reduce the time to lose lateral stability. This is more evident in cases of lower load ratios than the higher load ratios. The numerical study presented in this paper involved building a finite element model to simulate the columns behaviour in fire. The model was validated using the test results obtained from unrestrained and restrained columns fire tests. The model demonstrated good agreement in the prediction of failure times and failure mechanisms of local and overall buckling. The FEM model was then used to conduct a parametric analysis involving factors of slenderness, restraint and loading. The conclusions drawn for this research are presented at the end of the paper.

KEYWORDS

Elliptical, Columns, Steel, Fire, Restraint, Buckling

1. INTRODUCTION

In spite of the increasing use of elliptical hollow steel sections in buildings (due to their aesthetically pleasing shape compared to rectangular and circular hollow sections), there are limited researches carried out on the performance of columns with elliptical sections under fire conditions especially with axial restraint. The growing trend in the construction industry to use elliptical hollow steel sections in buildings requires more research investigating the performance of structural elements with elliptical sections. There is however very limited research carried out on the performance of the elliptical columns under fire conditions especially with introduction restraint boundary conditions. In recent years, research has investigated the performance of other hollow sections available (circular, rectangular and square) under loading and fire conditions.

2. THE EXPERIMENTAL PROGRAMME

The rig (see Figure 1) used during testing allows for loads to be applied to the columns and can provide axial restraint using the rig stiffness. The facilities also allow, measuring thermocouple temperature readings, axial

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and lateral displacements using LVDT's. The test programme involved testing columns with 2 oval sections 200 × 100 × 8 mm (EHS-A) and 300 × 150 × 8 mm (EHS-B) of length = 1800 mm, yielding 2 slenderness λ = 51 and 33. The columns were tested under loadings levels of 0.2, 0.4 and 0.6 of the ultimate strength for the hollow elliptical section EC3 under axial restraint αk ranging from 0 to 0.16. The degree of axial restraint αk is defined as:

$$\alpha_k = \frac{K_s}{K_c}$$

where Ks is the stiffness of the surrounding structure (rig), Kc is the axial stiffness of the column

$$K_c = \frac{AE}{L}$$

Where, A is the column section area; E is the Young modulus and L is the length of the column. The loading imposed on columns was increased gradually in equal time steps to allow the column to settle and to get stable readings. Once the load level was reached the burner was ignited subjecting the columns to a hydrocarbon fire Ali et al. [8]. The columns were with pin ended supports at the top and the bottom by using half-moon steel bearings at each end. To reduce the friction at the supports, graphite tape was incorporated between the two steel surfaces to provide lubrication. The thermocouples were located throughout the length of the column to measure the temperatures at 250 mm from the top and 250 mm from the bottom of the column as well as at the mid height of the column. Four thermocouples were placed around the outside of the column as shown in Figure 1.

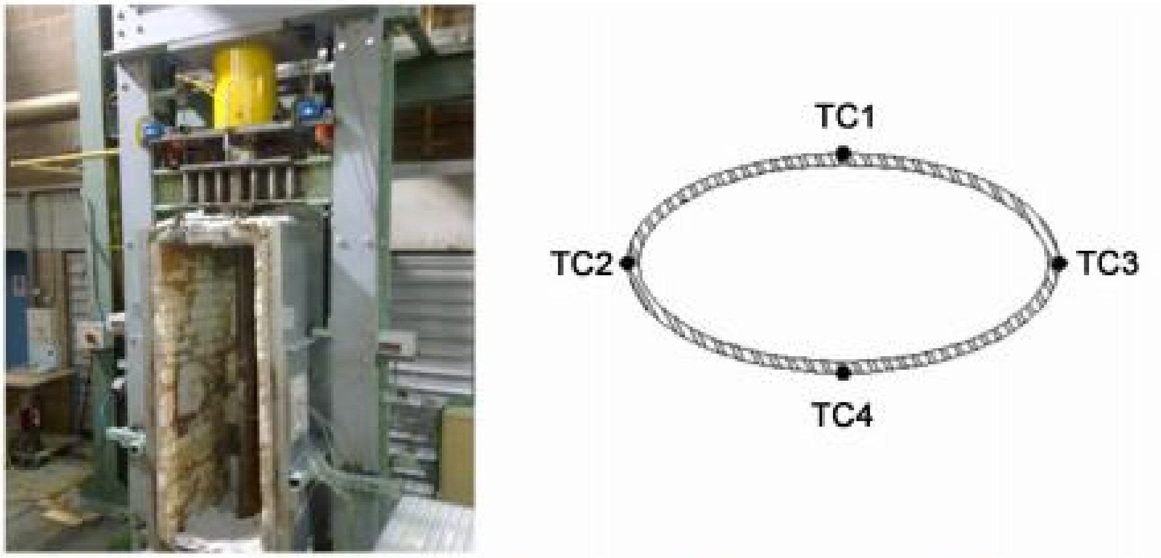

Figure 1. (Left) Testing rig, (Right) Thermocouple locations for the elliptical steel columns.

3. TEST RESULTS

3.1 UNRESTRAINED ELLIPTICAL COLUMNS

The data of axial and lateral displacements obtained from the tests are shown in Figure 2 for EHS-A (slenderness λ = 51) and Figure 3 for EHS-B (slenderness λ = 33). The results for column EHS-A show that as

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the load ratio is increased the time for loosing lateral stability drops from 13mins for 0.2 loading, to 10mins for 0.4 and to 8mins for 0.6 loading. The same relationship can be seen from the results for the EHS-B where the time of failure by losing lateral stability drops from 13mins for 0.2 loading, to 10mins for 0.4 to 8 min for 0.6 loading. By comparing the two sets of data, it can be seen that the columns responded to heating in a similar way as the axial displacement increased linearly as the time increased. When the column reached the maximum axial displacement it started to fail slowly at first (due to degradation in the steel properties under high temperatures), then the deformation started to increase more rapidly towards complete failure. This can be observed more clearly in the load levels of 0.6 of the ultimate loading as there are approximately 30 seconds between the peak deformation and the columns failure where as it takes the 0.2 loaded columns between approximately 1min 30 secs to 2mins.

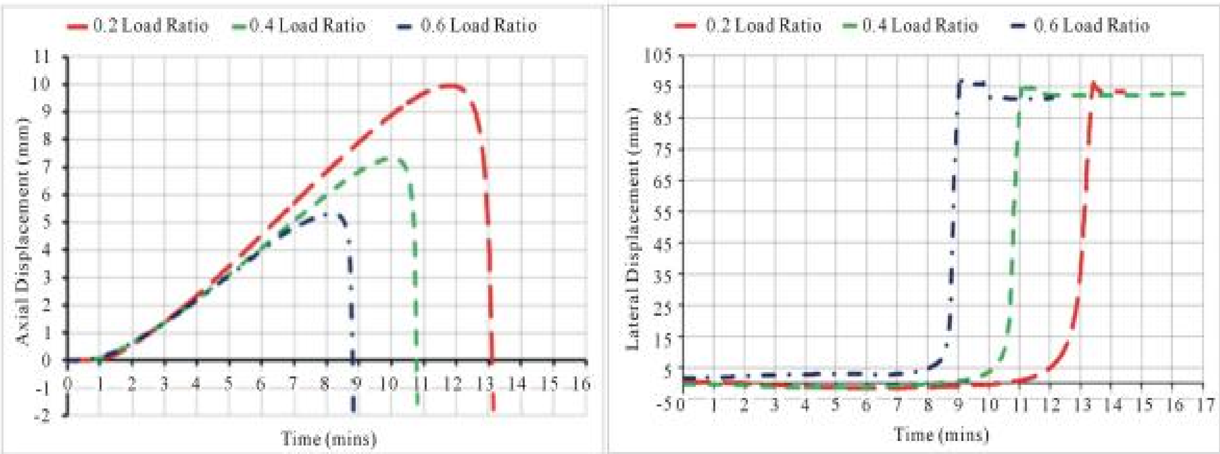

Figure 2. Development of lateral and axial displacements for unrestrained columns 200 × 100 × 8 (EHS-A), (left) axial displacement, (right) lateral displacement.

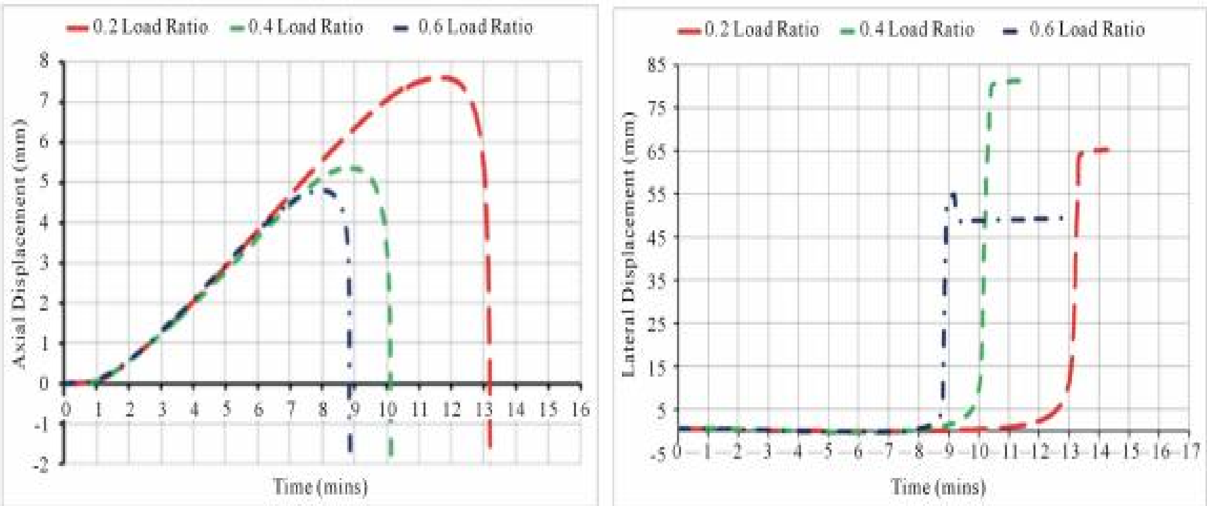

Figure 3. Development of lateral and axial displacements for unrestrained columns 300 × 150 × 8 EHS-B, (left) axial displacement. (right) Lateral displacement.

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Two sections demonstrated the same fire resistance time for each of the different loading levels regardless of the size of the section. Figure 2 and Figure 3 show a consistent correspondence between the development of lateral and axial displacements under high temperatures.

3.2 RESTRAINED ELLIPTICAL COLUMNS

In the case of the restraint tests the same load ratios of 0.2, 0.4 and 0.6 were applied to the columns as in the unrestrained tests. The restraint provided during the tests was imposed by the stiffness of the testing rig with the addition of rubber springs which help to provide a range of rig stiffness (Figure 4). The displacements obtained during the tests show that the EHS-AR (slenderness λ = 51) failure time (due to loosing lateral stability) decreases with the increase of loading level from 10mins for 0.2, to 8 mins for 0.4 and to 6 mins for 0.6 (Figure 5). The same relationship can be seen in the larger EHS-BR (slenderness λ = 33) section, 10 mins for 0.2, to 9 minutes for 0.4 and to 8 minutes for 0.6 (Figure 6). It can be observed from the data that the time to failure from the point of maximum axial displacement increases with the rise in the load ratio applied to the section due to the frictional forces generated at the supports. The results indicate that the failure by losing lateral stability of the EHS-BR tests occurs gradually when the load ratio increases if compared with the smaller EHS-AR section. This can be attributed to the high frictional forces being generated at the half moon supports for the larger sections as the load applied is greater than that of the smaller section. As both of the sections were subjected to relatively the same axial restraint then this may be a feasible reason for this observation.

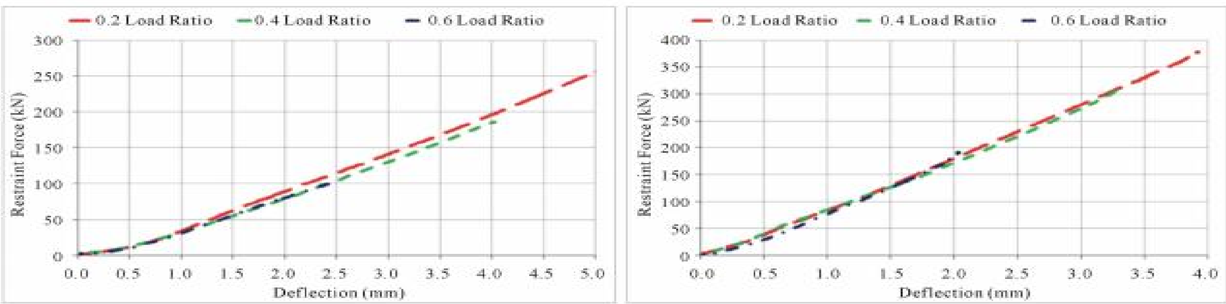

Figure 4. Restraint forces vs. displacement for restraint tests, (left) EHS-AR (slenderness $\lambda = 51$), (right) EHS-BR (slenderness $\lambda = 33$).

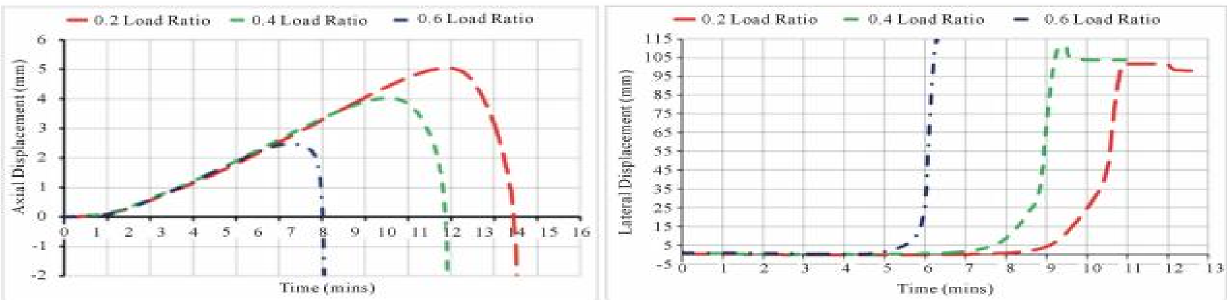

Figure 5. Development of lateral and axial displacement for restrained columns 200 × 100 × 8 EHS-AR, (left) axial displacement, (right) lateral displacement.

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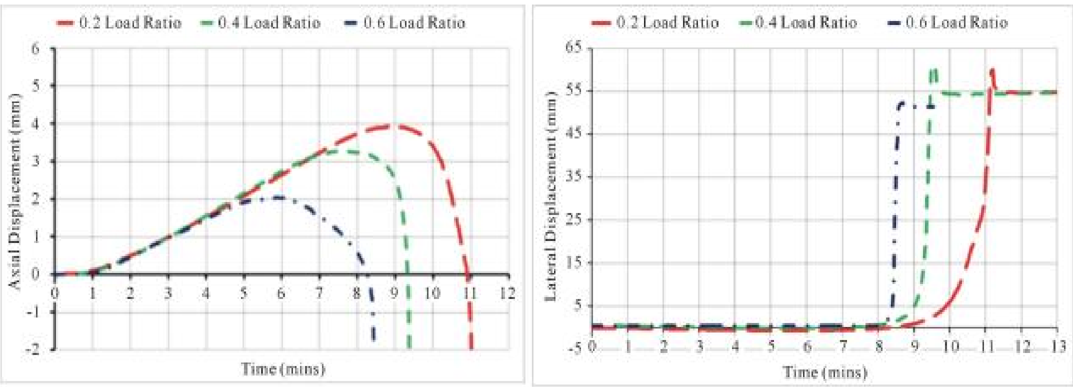

Figure 6. Development of lateral and axial displacement for restrained columns 300 × 150 × 8 EHS-BR (slenderness $\lambda = 33$), (left) axial displacement, (right) lateral displacement.

3.3 TESTS SUMMARY

In each of the tests the lateral displacements of the columns were recorded using quartz rods Connected to the LVDTs. The columns are deemed to have failed laterally when the column has deflected by more than L/300, according to the EC3 which in this case is 6 mm. The second failure criteria adopted is when the column falls below the datum zero line recoded before heating and after loading. The results of both failure criteria and axial displacements of the unrestrained columns are shown in Table 1.

In general the restrained columns demonstrated lower fire resistance than the unrestrained columns and the results are shown in Table 2. It is important to emphasize that the two adopted failure criteria of lateral and axial displacements converge under high loadings.

When comparing the overall buckling and local buckling failure mechanisms shown in Figure 7 it can be seen that both sections failed in a similar mode, regardless of the degree of axial restraint imposed on the column, with some difference in the local failure which can be attributed to the classification of the section.

As the EHS-B is classified as a slender section it is deemed to be more susceptible to localized buckling than in that of the compact EHS-A.

Table 1. Summary of unrestrained columns test results for elliptical columns.

Section	Load Ratio	Load (kN)	Time to Failure (mins)		Maximum Axial Displacement (mm)
			Axial	Lateral	
200 × 100 × 8 EHS-A	0.2	212	13	11	9.94
	0.4	424	10	10	7.31
	0.6	616	8	7	5.31
300 × 150 × 8 EHS-B	0.2	354	13	12	7.61
	0.4	701	10	9	5.36
	0.6	1053	8	8	4.81

Table 2. Summary of restrained columns test results for elliptical columns.

Section	Load Ratio	Degree of Axial Restraint α_s	Load (kN)	Time to Failure (mins)		Maximum Axial Displacement (mm)	Maximum Restraint Force (kN)
				Axial	Lateral		
200 × 100 × 8 EHS-AR	0.2	0.12	209	10	8	5.04	257.032
	0.4		411	8	7	4.04	186.066
	0.6		637	5	5	2.47	100.745
300 × 150 × 8 EHS-BR	0.2	0.16	348	10	9	3.93	378.191
	0.4		697	9	8	3.27	305.585
	0.6		1052	8	8	2.04	191.431

Figure 7. Failure modes of overall and local buckling of the elliptical hollow sections. (a) EHS-A (slenderness $\lambda = 51$); (b) EHS-B (slenderness $\lambda = 33$).

4. CONCLUSION

The study has demonstrated that the maximum axial displacement of columns is less in the restraint tests compared to the unrestrained column. However, the maximum restraint force generated is greater when the load ratio is low. The study demonstrated that the failure of all columns can be by combination of overall and localised buckling occurring in the steel section where failure time decreased more as the loading level was increased. This is more evident in the larger section sizes. It was observed that by using variable with temperature thermal expansion coefficient and the EC3 thermal parameters, the FE model demonstrated reasonably good agreement with the experimental values of temperatures and excellent prediction of the mode of instability. The model has shown excellent agreements in failure modes of overall and local buckling. The study also highlighted the criticalness of the effect of geometric imperfections on the ultimate failure time and the fire resistance of the EHS column. The verified finite element model was used to conduct a parametric analysis involving parameters of loading level, restraint and slenderness. The parametric analysis has shown that the more slender the column, the lower the failure temperature. The parametric study has also shown a non-linear relationship between the loading ratio and the slenderness of the elliptical columns. Increasing the loading level from 0.2 to 0.8 has reduced the maximum displacement by 47% and decreased the failure temperature by 28%. In columns' slenderness range of 90 to 120, the effect of loading on failure temperature is less than that in the range of 60 to 90. It also showed a decrease in the axial displacements of columns if an axial restraint is imposed. The analysis has shown that increasing the loading decreases the axial displacement under fire and reduces the failure time of columns. The analysis also shows that the stockier the column is, the higher the generated axial restraint forces in fire.

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