The Effect Of Axial Restraint On The Fire Resistance Of Steel Columns

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ABSTRACT

The paper represents the outcomes of a joint research between the University of Ulster and the University of Sheffield into the performance of axially restrained steel columns during fire. The Ulster experimental program incorporates 37 high temperature tests that investigate three parameters: slenderness ratio (λ=49,75,98), degree of axial restraint (α_k=0, 0.1,0.2,0.3) and loading ratio ($\alpha_{L=}$0,0.2,0.4,0.6). A unique test rig which allows the application of both axial restraint and loads, either separately or at the same time has been especially designed for the experimental program. Typical results from the fire tests are presented, which illustrates characteristic response of the columns to the imposition of axial restraint, coupled with the temperature increase. In addition, trend graphs charting generic response are discussed. An associated computational study by Sheffield provides satisfactory accurate computer simulations of fire tests, using standard materiel property input data. The computer modelling exercises has been extended to parametric studies, to include the effects of many more levels of axial restrain. The linked experimental and computational study has thus validated a computational model, which can be used to provide the basis design guidance of the behaviour of restrained columns in fire situations.

KEYWORDS

Steel, Columns, High Temperatures, Fire, Axial Restraint, Finite Element, Computational Modelling

INTRODUCTION

Standards covering the design of multi-storey steel-framed buildings have always treated the continuity of individual columns within a structural frame in ways which are conservative rather than analytically correct. In ultimate limit state design at ambient-temperature, only end restraint due to the rotational stiffness provided by beams framing into the column as well as column continuity is considered as a boundary factor in design and the concept of effective length is a pragmatic way of taking this into account. In fire conditions Eurocode 3 Part 1.2 (1995) incorporates the effect of this rotational restraint, on a column whose material has softened considerably, by considering its effective length factor as 0.5. However, the other major effect on a column, which is either unprotected or partially protected against fire, is that it attempts to expand axially when heated. This expansion is resisted by the cumulative axial stiffness at the top of the heated column, which is created by the connection of upper floor beams and slabs to higher levels of the continuing column as well as the general shear stiffness of the structural layout as a whole. During the early stages of heating, the predominant effect on the column is its thermal expansion, and during this period the effect of restraint to expansion is that its axial compressive force is increased. As the temperature of the heated column rises further, however, this effect may be overtaken in significance by its compressive mechanical straining due to the increasing degradation of the steel stress-strain curves. At this stage its compressive force progressively reduces. Also, in more slender columns, premature instability may ensue as a net effect of the increasing load and the degeneration of mechanical properties. Thus, it is possible that continuity of the structure may impose adverse conditions in fire on isolated columns. However, if the upper storeys are capable of carrying the load by re-routing the vertical loading paths without themselves collapsing, then the axial force might in fact safely be redistributed. This appears to have been the case in the Broadgate Phase 8 Fire (1991), where the load originally carried by several internal columns seems to have been redirected by bridging action from lightly-loaded upper storeys towards columns nearer the perimeter. In cases where there is less strength in the upper storeys and more representative imposed load levels, it is possible that a genuine localised collapse may occur in the bays around and above a heated column's grid position.

In order to examine this behaviour over a range of column load ratios, slendernesses and degrees of restraint, as well as its implications within more extensive framed structures, a collaborative research project has been taking place since 1995 between groups at the Universities of Ulster and Sheffield. An experimental programme has been carried out in a purpose-designed facility in Ulster, and this has been supported by numerical modelling at Sheffield. It is the purpose of this paper to present an interim report on the studies.

The action of axial restraint was investigated numerically some time ago by Furumura and Shinohara (1976) and Cabrita-Neves (1995) who concluded that the imposition of an axial restraint significantly reduced the critical temperature. It was also noted that as slenderness increased so the reduction in critical temperature increased when a given restraining stiffness was applied. Recently, Franssen (1996) has sought to collate a database of column fire test information although is was realised that data from standard fire tests was somewhat inconsistent. Such deficiencies in the standard fire testing of columns have previously been highlighted by Witteveen *et al* (1981) and Pettersson *et al* (1979). It can also be argued that standard fire tests are unrepresentative of the real behaviour of columns in fires acting within frames. This situation makes the execution of a parametric experimental study linked to computational studies an attractive proposition. In the current test programme the influence of two principal factors has been investigated, the degree of axial restraint and the loading level. The load ratio α_L was defined in relation to the BS5950 ultimate load of the particular section under test and the axial restraint due to the surrounding structure was defined by expressing the structure stiffness k_S in relation to the column axial stiffness k_C by means of the restraint ratio $\alpha_K = k_S/k_C$. A schematic of the column related to its interaction with the surrounding structure is shown in Figure 1. A flexibility analysis, identifying structural interactions and leading to response equations, has been previously detailed by Simms *et al* (1996). The restraint ratios used it the test program were derived from experimental studies performed by Lennon (1994) on the Building Research Establishment's large building test facility at Cardington U.K., which revealed restraint ratios between 0.05 and 0.35 depending on column position, and the Broadgate Fire Report (1991) which found a range of restraint ratios between 0.01 and 0.35 (with a rogue value of 0.9).

THE TEST PROGRAMME

The experimental programme comprised a total of 37 fire tests and the full extent of the parametric study is illustrated in the test result summary held in Table 1 (33 tests reported). As alluded to above, the influence of two principal factors was being investigated, the level of axial restraint, α_K and the loading level, α_L. Three column sections were chosen to provide different slenderness ratios λ about the weak axis. Test columns were designed as essentially half scale, 1.8m long between pinned ends and the three standard sections, 152x152x23 UC, 178x102x19 UB and 127x76x13 UB, provided slenderness ratios of $\lambda = 49$, 75 and 98 respectively. This range gave good coverage of the slendernesses normally expected in multi-storey buildings; previous work by Simms *et al* (1996) examined the high slenderness of $\lambda = 152$. At each slenderness ratio four different load levels were applied $\alpha_L = 0$, 0.2, 0.4 and 0.6 and all load levels were tested in conjunction with 3 different levels of axial restraint, $\alpha_K = 0$, 0.1 and 0.2, providing a reasonable cover of the measured values referenced previously.

The major feature of the test rig, illustrated in Figure 2, was its ability to apply a direct axial load to the column specimen, whilst at the same time providing degrees of axial restraint, which were variable and whose magnitudes could be recorded independently during the fire test. With reference to Figure 1, concentrating initially on the provision of axial restraint due to structural frame action, the frame of the rig itself including the lower beam, the two side columns and the lateral beam (1) provides the maximum restraint stiffness available in the test setup. This provided a stiffness in excess of $\alpha_K = 0.3$ for the smallest section (UB13) and was of adequate stiffness to provide $\alpha_K = 0.2$ for the heaviest section (152UC). Control of the application of the restraint was by means of adjustment of the position of the lateral beam (1) by means of the threaded bars (5), which enabled sensitive definition of the restraint boundary conditions, by simply hand tightening restraining nuts, normally invoked once the test loading had been applied. Other lesser restraint stiffnesses were provided by the addition of rubber springs (4) within the framing loop at the two symmetrical points of contact with the threaded bars. It was also at these positions that load cells (2) were introduced to measure the magnitude of restraint stiffness as the test progressed. Application of the test load was introduced by means of a hydraulic ram system (3) reacted from the test rig above and again continuously monitored through load cells. The rams were actuated using pressure control and were able to retract, maintaining load but not increasing it, as the column expanded under heating: however it was more difficult to maintain loading, following a sudden drop in column head displacement, as instability was generated. Every effort was made to ensure symmetry of the system about the weak (y-y) axis of the system. Also, although the rig was essentially two dimensional, additional cross beams (alluded to at 6) applied to both top and bottom (not shown) lateral beams were found necessary to restrict torsional movement at the supports about the section major (x-x) axis. The rig was thus capable of application of load only, without frame stiffness applied (α_L = value, $\alpha_K = 0$); restraint stiffness only without load ($\alpha_L = 0$, α_K = value) or a combination of both applied loading and restraint (α_L = value, α_K = value).

Table.1 Experimental test program and results

		$\alpha_K =$ 0		$\alpha_K =$ 0.1		$\alpha_K =$ 0.2	
SECTION	α_L	Max. Force	Collapse Temp.	Max. Force	Collapse Temp.	Max. Force	Collapse Temp.
UC23 λ =49	0	0		355	N/A	465	N/A
	0.2	0	701	326	640	452	583
	0.4	0	626	285	598	377	517
	0.6	0	557	189	547	236	363
UB19 λ =75	0	0		325	552	381	507
	0.2	0	644	299	555	333	455
	0.4	0	629	249	466	254	432
	0.6	0	539	153	364	201	408
UB13 λ =98	0	0		209	445	268	530
	0.2	0	717	201	536	228	441
	0.4	0	658	155	333	209	410
	0.6	0	567	112	386	158	336

Test columns were 1.8m long, with end plates attached, which could be assembled into half round graphite lubricated end bearings, which gave a quasi pinned end condition about the weak (y-y) axis and a flat-bearing type feature about the strong (x-x) axis, which provided appropriate end rotational resistance. Consideration was given to the possibility that bearings could produce unwanted frictional rotational resistance, reducing effective lengths. Presently it is assumed that this has less significance because of the rates of testing, for various reasons, but the problem is acknowledged and is under current investigation. During the test, two significant displacements were measured, the lateral displacement (D1) on the weak axis at column mid-height and the column axial extension (D2). Both displacements were measured using LVDT's positioned from an independent reference frame, the lateral displacements being accessed by means of quartz rods located through the furnace. Temperatures were measured at 4 locations on the length of the column and at 5 points on a cross-section as indicated on Figure 2 and good uniformity of temperatures were achieved, noted as only 5-6% variation on the maximum temperature longitudinally at 750 °C. The furnace was a simple rectangular box of internal dimensions 600mm square by 1700 mm long and suitably enclosed the bulk of the length of the test specimen, with the bearings external. Heating was by a single burner source fired at a single rate, resulting in a natural heating rate of the enclosed void, which created a bi-linear (with transition) time-temperature curve, illustrated in Figure 3, having an initial fast heating rate up to about 350 °C emerging into a slower steady heating rate thereafter. This was convenient for data acquisition purposes as a suitably large temperature was reached quickly but a reasonably slow heating rate was achieved within the band of failure temperatures of the test columns (15 °C/min at 400 °C to 2 °C /min at 650 °C). Notably, it was not thought necessary to conform to a Standard time temperature curve such as BS476, and heating rates were not identified a major issue as it was considered that creep effects were not dominant.

The test procedure was in two parts, firstly an ambient temperature incremental load application was adopted to the prescribed load ratio, load and displacement only being measured. After this the designated restraint, if any, was initialised, by tightening of the nuts on the threaded bars. Thereafter, a full data acquisition scheme was implemented for the duration of the heating regime. As the test progressed the applied load was maintained at a constant value, until a rapid drop off in axial displacement ensued as a result of material degradation and/or instability.

TEST RESULTS

Typical test output graphs are illustrated in Figures 4-7, for two different test scenarios on two different columns, which express reasonably extremes of behaviour. Figures 4-5, a, b & c detail response with temperature, of restraint force, axial displacement and lateral displacement. The UB13 specimen (λ=98) was the highest slenderness, with $\alpha_K = 0.2$ and $\alpha_L = 0.2$ and the UC23 test (λ=49) represented the lowest slenderness, with $\alpha_K = 0.2$ and $\alpha_L = 0.6$. In both cases the increase in restraint force was quite linear up to close to the maximum value, where the rate of increase tended to tail off due to degradation of material properties. In the more slender member (Figure 4) sudden instability occurred at peak restraint, accompanied by an associated reduction in axial displacement, the instability being highlighted by the sudden increase in lateral displacement. However, it is noticeable that equilibrium recovered at a point before full restraint was alleviated and it could be argued that the column was still functional at this stage as it was still holding the original load for which it was designed. So, is the failure temperature linked to the original instability (441 °C) or to the point where the original load could no longer be carried (500 °C)? In the less slender specimen (Figure 5) it can be seen that the additional restraint did not provide instantaneous instability but the degradation in column response permitted the restraint force to be removed from the column at a controlled rate. However, the lateral displacement graph tends to indicate that this was achieved by lateral movement of the column rather than reduction in axial stiffness (driven by reduction in effective modulus) - the column found new positions of equilibrium as it deflected laterally. The column then did effect a sudden instability shortly after the full restraint force was reduced to zero - as at that point the column was required to carry the constantly applied load, which was a position that it could not sustain - signified by a large lateral displacement.

The output from each test allowed an evaluation of the actual restraint stiffness applied in each test, by plotting the restraint force generated against column extension. Graphs 6-7 show that the spring system behaviour was adequately linear and almost similar on unloading, the small hysteresis in Figure 7 being due to a small rotation in end bearings about the column major (x-x)axis, which was corrected in most of the rest of the tests by redesign of the rig to include a quasi-3-D stiffness. The other aspect of test behaviour, which could not be corrected, was lack of fit, mainly due to bedding in at bearings. This was most evident in that the restraint force did not immediately increase linearly with temperature at the start of the test. This gap seems not to have had a major effect on the maximum restraint force generated (Model-no gap, Fig 4), and it could be argued that the restraint force simply required additional temperature to ensure growth to its maximum possible level, until restricted by the other factors discussed earlier. There was obviously then a non-conservative record of the maximum temperature achieved before the onset of failure. A simple explanation as postulated above is probably satisfactory enough to give a coarse estimate of restraint force, but the interaction is more complicated than that, and one would expect that a small reduction in restraint force would also ensue as the generation of restraint force was being controlled by a proportionally higher temperature throughout the duration of the test. This is so and test results with lack of fit can be adequately modelled using simple flexibility equations (Simms *et. al.* (1996)) or computer modelling (Bailey *et. al.* (1995)).

The tests have also been analysed using VULCAN (Bailey *et. al.* (1995)) and the computer modelling exercise is described in detail later. The results are incorporated in Figure 4 and it can be seen that the computer models represent the test responses shown very adequately indeed. Lack of fit has also been incorporated and computer simulations are applicable generically, using standard initial assumptions and material property response information. There are some deviations from test data, mainly at the point of instability achieved in the test results. In this region the computer simulation initially seems to respond in a stiffer fashion to the tests and instantaneous instability is not achieved. In particular at higher, slendernesses it is considered that a dynamic effect occurs generally in the test response. Under steadily increasing loading, a small rotational friction in the bearings restrains the effective length to less than unity and a higher critical load than could be sustained by a simple pinned end column, but once instability occurs the rotational restraint dynamically releases, resulting in runaway lateral displacement and immediate and sudden drop off in load capacity.

A summary of all test results -maximum restraint forces and collapse temperatures are held in Table 1 and the trends in this information are presented in two ways. Figure 8 illustrates the relationship between maximum restraint force generated and restraint ratio α_K and column size. It can be seen that restraint force increased considerably to the first degree of axial restraint $\alpha_K = 0.1$ and then the increase was much less marked to the second level $\alpha_K = 0.2$. More restraint force was generated in lightly loaded columns and reduced in load ratio order within each column range. More restraint force was generated in the more stocky columns (UC23), but these columns also had the largest area. The observations simply give a feel for trends, but it is considered that a more detailed analysis , presenting the information is specific terms, would be somewhat complicated by the myriad of controlling interactions within the generic behaviour.

Trends in failure temperatures are also presented, in Figure 9. Definition of failure in fire is a complex issue, but in this case it has been decided to define column collapse as the first point of observed instability. The case for extending this definition, particularly to slender columns, has been presented earlier. Furthermore, failure in fire should also be addressed within the context of the possibility of offloading due to load redistribution, as discussed in the introduction. However, this is considered to be a separate issue with respect to the present test results, deemed to being more appropriate to specific consideration within the total design process. Different trends may be observed in Figure 9. In the more slender columns (b)(c) a small degree of axial restraint resulted in a large influence (lower) on failure temperature, whereas further increase in restraint had a lesser impact. This effect was very noticeable in even more slender columns (λ=152 (Simms, *et. al.* (1996)). The trend in the stocky columns (a) was the reverse, the first restraint level ($\alpha_K = 0.1$), having virtually no influence on failure temperature even at a high load level ($\alpha_L = 0.6$), with a large impact at the next restraint level ($\alpha_K = 0.2$). Trends in results were remarkably consistent, even though anomalies seemed apparent in the comparisons of some results at lower slenderness between the two stiffness ratios, where the failure temperatures increased as the restraint ratio increased. These inconsistencies may be attributed generally to the complexities of the test method and the sensitivity of response to temperature, particularly taking into consideration lack of fit issues, and differences in initial curvature recorded between tests may have been an additional factor.

MODEL RESULTS

The software used to investigate column behaviour was the VULCAN program (formerly known as INSTAF) developed at Sheffield University (Bailey *et. al.* (1995)). It is a non-linear finite element analysis code capable of analyzing steel / concrete composite frames with semi-rigid connections at elevated temperatures.

The analyses of the heated column have been carried out using eighteen finite elements to represent the column as shown in Figure 10. This has been shown in previous studies to be easily enough for an accurate representation. A rotational spring element was placed at each end to represent a pin-ended restraint. In addition, the spring element at the same end of the column as the applied load was given purely elastic, bi-directional axial spring characteristics. The elastic stiffness of this axial spring was varied to give the required restraint factor.

The strut was given an initial geometrical imperfection, applied load, section dimensions, material properties and temperature profiles as recorded in the tests. Nine temperature profiles were used to accurately represent the heating regime imposed on the column as shown below. The temperature data from the tests was matched at the relevant places (profiles #2 & #8) and linear interpolation used to calculate the temperature at other places along the length of the column and across the cross-section.

For this paper, the Ulster test columns of slenderness 49 (using 152x152x23UC sections) were modelled with the 4 load levels (0.0, 0.2, 0.4 & 0.6 x Design Load) and the 3 restraint factors (Alpha = 0.0, 0.1 & 0.2). The results are shown in the form of Force vs Temperature Graphs in Figure 11. As can be seen, the results fall into two groups, those with restraint factor 0.1 and those with 0.2. The behaviour of each group is similar, the higher the applied load, the less restraint force is required to start to return the column to its original position.

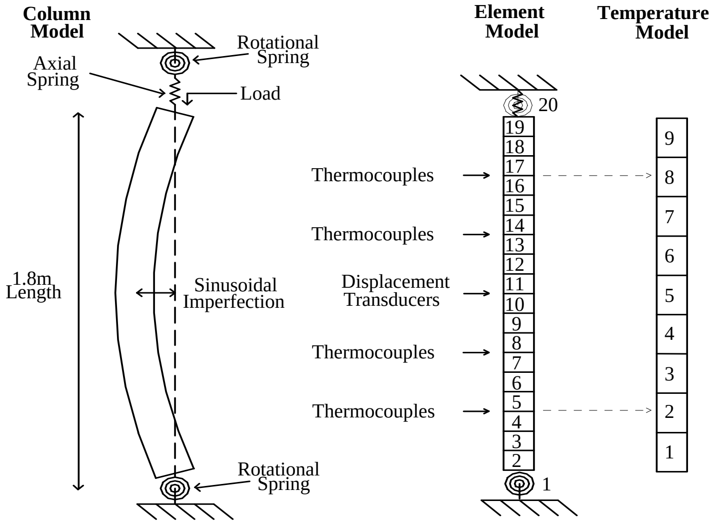

Figure 10. Basic Column Model

The columns with the higher restraint factor increase their restraint force more, for a given increase in temperature, than columns in the other group. They also reach a higher value of maximum restraint force, which can be achieved since the column is cooler and so stronger than when the other group is at maximum force. The test data for the lower restraint group has been plotted on top of these results and shows a very good comparison with the model results. It also suggests that the restraint applied by the rig is slightly less than that assumed in the model.

EXTENDED INVESTIGATION

The above investigation has been simplified by choosing one load level (0.2 x design Load) and assuming a uniform temperature distribution both across and along the column. It has also been extended to include many more levels of axial restraint. The vertical deflection of the top of the columns is shown in Figure 12. The results show that columns with more axial restraint reach a lower peak axial displacement. This is because, for a given amount of axial expansion, the restraint force is much higher. This also explains why the peak displacement occurs at a lower temperature in these columns, since axial expansion and temperature are linked via the expansion coefficient. All the columns pass through their original position at 725 °C. This is expected to happen at the same point for all the columns, since, when at their original position, the restraint spring is not extended and so its stiffness is irrelevant. After this point, the load starts to be carried by the restraint spring and so the column can survive indefinitely by shedding more and more load onto the spring as its own strength decreases. The level of axial displacement when this occurs is directly linked to the stiffness of the spring and so is higher for cases with less axial restraint. This post-failure load shedding would be seen in heated columns in framed buildings where load would be carried by surrounding beams. However, unlike the spring model, these beams would have an ultimate strength. Shedding too much load onto the beams would eventually cause structural collapse.

CONCLUDING REMARKS

An experimental fire test programme has been carried out on a total of 37 steel columns specimens, subjected to both applied load and restraint forces. The following general responses were observed.

The fire resistance of the columns was reduced by the imposition of restraint, and increasing the axial restraint increased the value of restraint force generated and reduced the failure temperature, for all values of slenderness tested. The magnitude of additional restraint force generated decreased with increasing load ratio. Also, lightly loaded columns experienced high additional restraint forces, which could greatly impair their actual design capacity in fire. Increased restraint force was generated in more stocky columns, but onset of failure in these columns was more gradual than in slender columns, where failure due to instability was sudden.

Finite element modelling provided a good simulation of column behaviour in fire tests and any lack of accuracy can be attributed to changing test support conditions. Initial computational parametric studies of generic behaviour show potential and are commended as a basis for the provision of design guidance.

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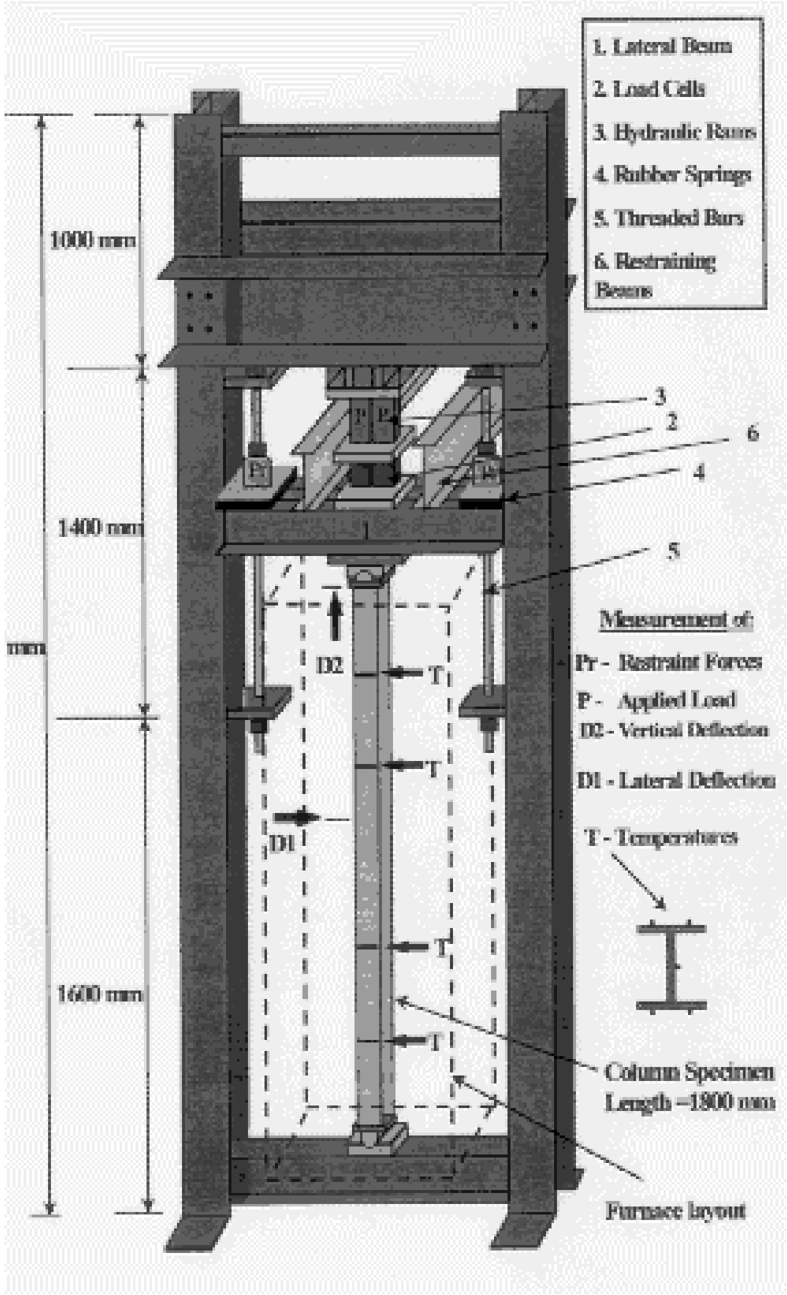

Figure 2 Axial Restraint Test Rig

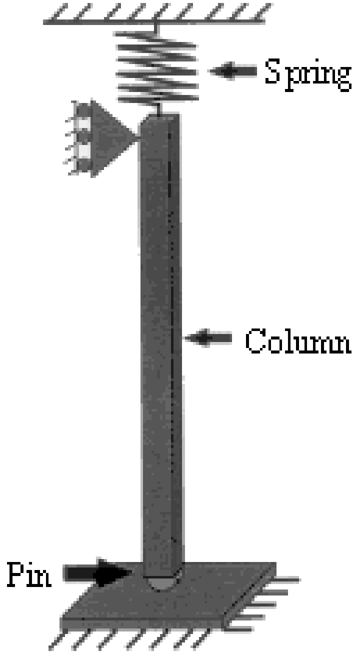

Figure 1 Idealisation of Test Column

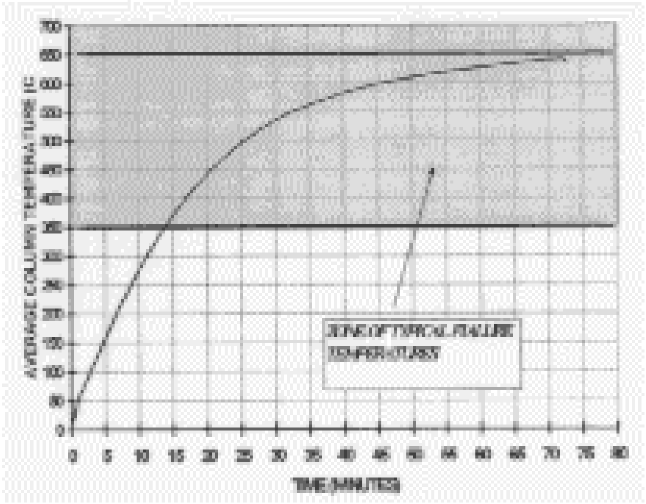

Figure 3 Typical Heating Regime

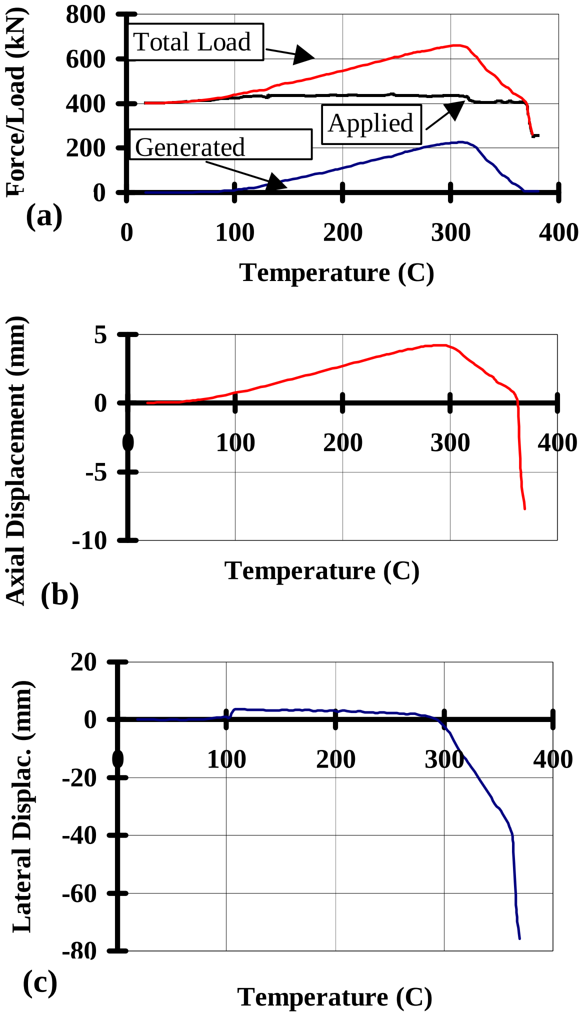

Figure 5. Test results, column 11UC23

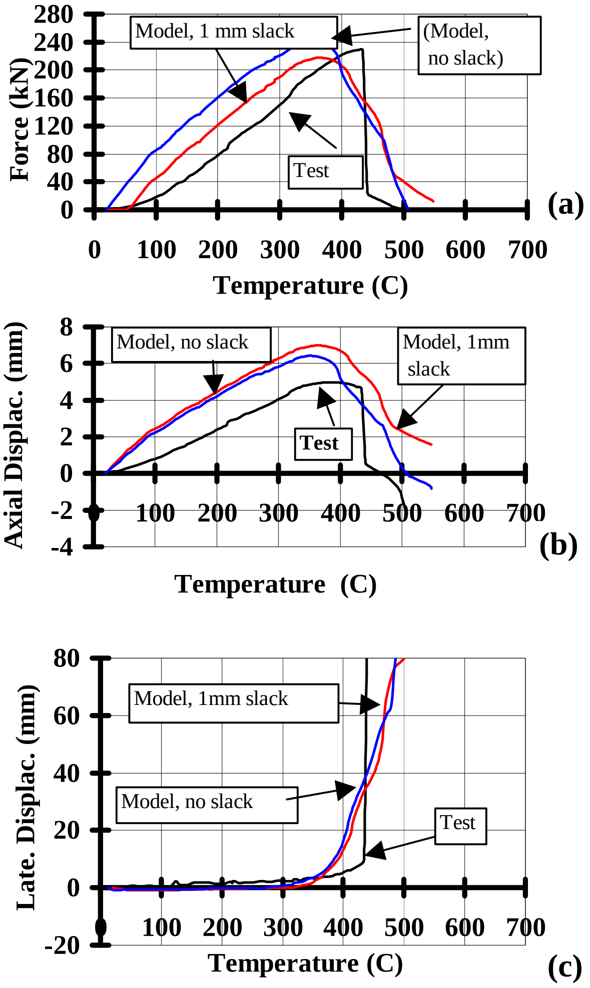

Figure 4. Test results, column

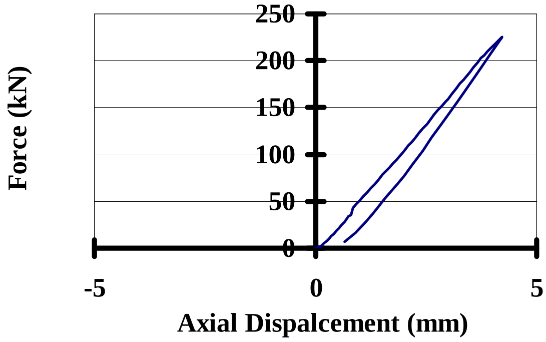

Figure 6. Spring stiffness used for

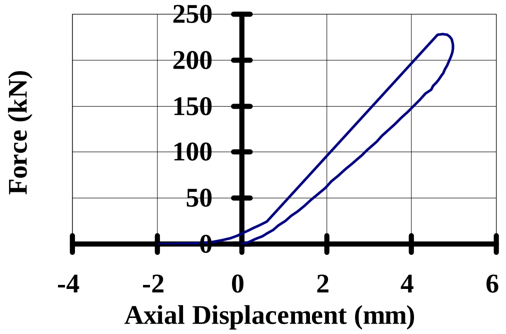

Figure 7. Spring stiffness used for

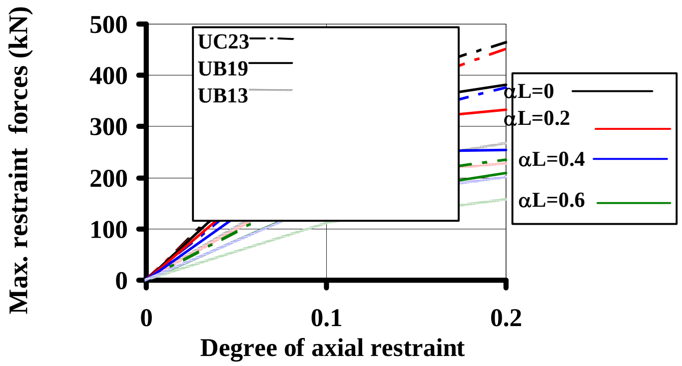

Figure 8. Maximum forces generated

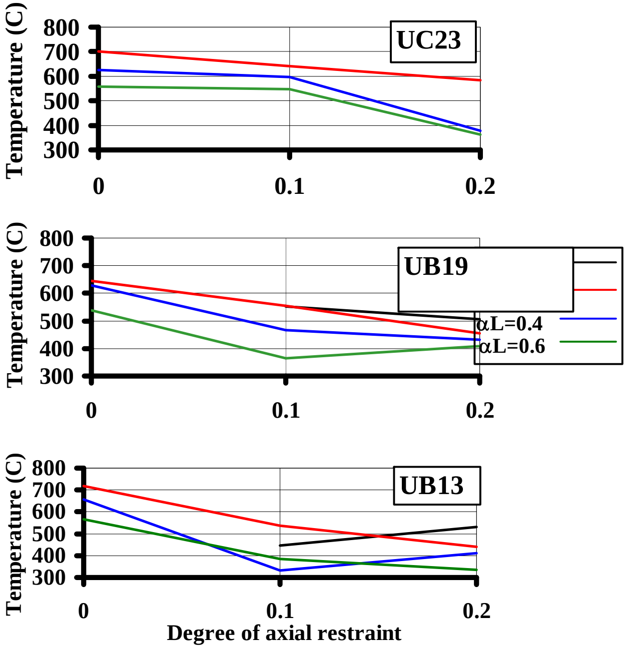

Figure 9. Collapse temperatures of columns

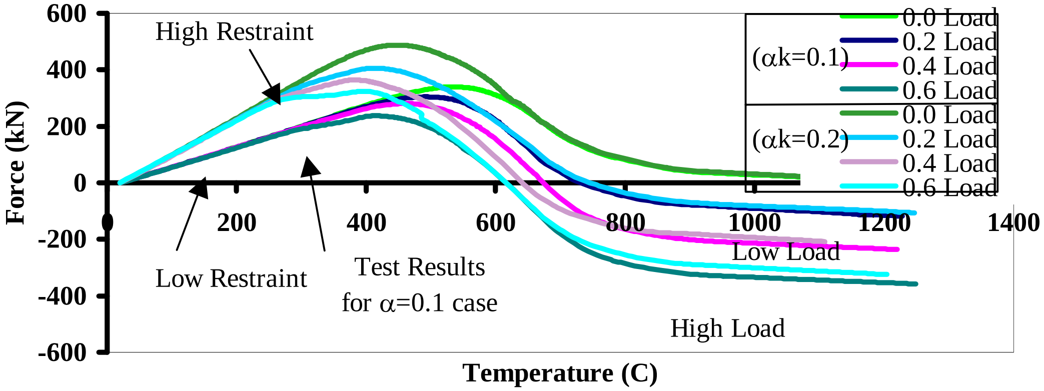

Figure11. Restraint force in Ultser column models

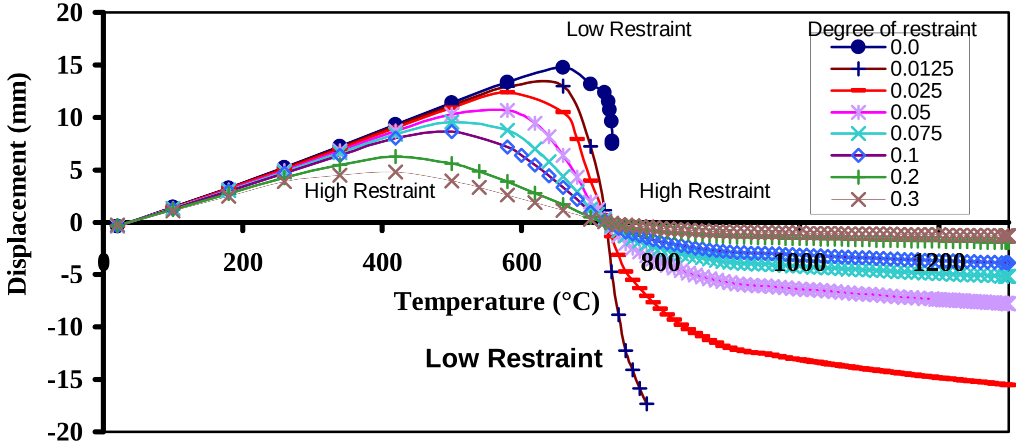

Figure 12. Vertical dispalcements in column models