A Model Fire Test for Parametric Testing of Half Scale Structural Components

D.J. O'CONNOR, B. MORRIS and G.W.H. SILCOCK
Fire Engineering Research Centre
School of the Built Environment
University of Ulster
Newtownabby, Co. Antrim, N. Ireland, BT37 0QB, UK

ABSTRACT

The full scale fire resistance test forms the basis of acceptance of structural integrity in fire. However, such tests are expensive and provide only limited test data of parametric significance required for research purposes.

In this paper a methodology for the fire testing of reduced scale structural models is presented for discussion. The principles of scale modelling applied to both structural testing and thermal modelling are detailed. This requires the imposition of a double incident heat flux and quarter time scale rule creating a new fire curve for a half scale model test. The increased flux requirement is accommodated by an enhanced temperature axis by consideration of convective and radiative surface heat transfer processes. An alternative suggestion to control model test furnaces by heat flux instrumentation is postulated.

Finally, experiences with the application of the methodology to studies on steel and concrete columns, brickwork compartment walls and reinforced concrete floor slabs in standard fire tests are presented.

KEYWORDS: Scale Modelling, Fire Testing, Heat Transfer, Masonry

NOMENCLATURE

a = absorptivity, ( )
Cp = specific heat capacity, (J/kg K)
d = thickness of specimen, (m)
h = heat transfer coefficient, (W/m^2 K)
k = conductivity, (W/m K)
L = length, (m)

P = applied load, (kN)
P_y = applied load at yield (kN)
q = flux, (W/m^2)
s = scale factor, ( )
T = temperature, (K)
ΔT = temperature difference (K)
t = time, (s)
u = thermal extension, (m)
x = displacement, (m)
y = lateral bowing deflection, (m)

α = coefficient of linear thermal expansion,($^\circ$ C^{-1})
ϵ = emissivity, ( )
γ = thermal diffusivity, (m^2/s)
λ = slenderness ratio, ( )
ρ = density, (kg/m^3)
σ = Stefan Boltzmann Coefficient, (W/m^2 K^4)

Subscripts
f = of the furnace
m = of the model
n = net
o = of the centre
p = of the prototype
w = of the wall

INTRODUCTION

Quintiere [1] recently stated, "A deliberate strategy of scale modelling based on the governing laws of physics is both an essential and practical means of obtaining general results"

The full scale fire resistance test forms the basis of acceptance of structural integrity in fire. Full scale tests are expensive and test programmes conducted solely for the purpose of research investigations are limited, most element testing being conducted for commercial validation. Extrapolation of test data or parametric studies are now often conducted using computer simulations. However, there is a real need to base principles of engineering behaviour on physical evidence. In other fields of structural engineering, model studies are often employed as a cost effective means of producing test data. It is on this basis that the proposed model fire test methodology is presented. The principles of scale modelling are detailed and their application to the formulation of a new model fire curve for half scale modelling defined. Finally, the application of the methodology to studies on brickwork and concrete compartment walls, concrete floor slabs and steel columns are demonstrated.

REVIEW OF FIRE TESTING AT REDUCED SCALE

The modelling of the fire resistance test was examined by Sahota and Pagni [2] and McGuire, Stanzak and Law [3]. Both noted that modelling of the conduction process was controlled by the Fourier Number, but acknowledged that surface heat transfer posed difficulties. The former attempted to isolate the significant contributions from the Biot and Stefan numbers and suggested several methods of physically altering the furnace environment to produce appropriate output. The latter suggested an alternative empirical alteration to the time squared rule ($t^{1.6}$) for half scale modelling. More recently Ng, Ah Book [4] et al. applied some of the previous thinking to model testing of reinforced concrete columns. However, no account was made for surface heat transfer. Result quality was deemed to be good although accuracy became problematic at 1/3 scale.

The current proposals have been evolved within a 3 year project sponsored by the UK, Engineering and Physical Science Research Council, and described in earlier [5] and recent [6] key papers. This paper details and promotes the methodology and gives several examples of its successful application.

MODEL ANALYSIS APPLIED TO STRUCTURAL FIRE TESTING

The model test methodology was first implemented to consider the behaviour of half scale compartment walls subjected to a heat source on one side, the objective being to accurately predict free thermally induced structural displacements. This investigation permitted the basic criteria for scale modelling of a thermal environment to be realised. Thence, the general application to axially loaded walls and columns, including buckling, and beams loaded in flexure has been formulated.

Thermo- Structural Behaviour

Consideration of thermally led displacements in compartment walls permits the isolation of the two significant thermo-structural degrees of freedom expressed by the free extension and bowing equations namely:

Translation: free extension: $$\left[\frac{u}{L}\right] = [\alpha\, T_o] \quad (1)$$

Rotation: free bowing: $$\left[\frac{y}{L}\right] = \frac{1}{8}\left[\frac{L}{d}\right][\alpha \Delta T] \quad (2)$$

The equations have been written in the form of dimensionless groups. This highlights the controlling parameters as average temperature T_o (extension) and difference in temperature across the section thickness ΔT (bowing), assuming that the coefficient of linear expansion α is consistent between model and prototype. It can be concluded that for dynamic similarity both controlling parameters T_o and ΔT must be maintained between model and prototype. This leads to the first criterion for model testing, the *normalised temperature distribution*, shown in Figure 1. Similarity requires the same temperatures to be maintained everywhere between model and prototype, ie. at normalised positions through the thickness.

In the main, this criterion has satisfactory implications in that all temperature dependent properties at elevated temperatures are correctly modelled. In particular, reduction in strength

T_w = Temperature of the extreme fibre

T_R = Temperature of possible reinforcement

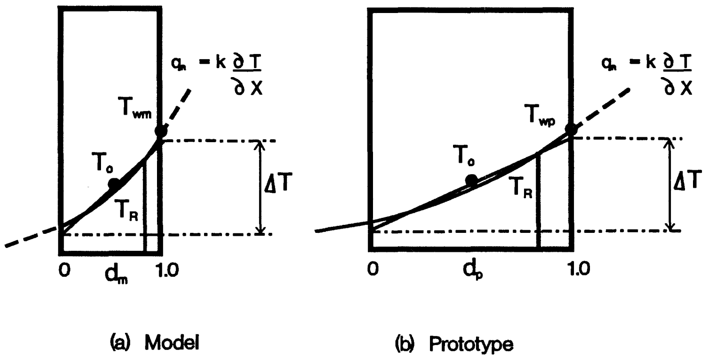

FIGURE 1: Normalised Temperature Distribution

of extreme fibres and steel reinforcement is not compromised. However, the increased temperature gradient in the model may introduce errors in size effects, particularly relating to free moisture transportation, and also have implications on spalling.

Geometry and Structural Response

As is normally the case in physical modelling all dimensions should be scaled, so the slenderness ratio $\lambda = L/d$ is maintained and displacements should be defined in specific terms (u/L, y/L). In reinforced concrete slabs, bar diameter, spacing and cover distance should be scaled.

Application of load in axial or flexural situations should be recorded in terms of stresses and related to yield strength, so that the load ratio (P/P_y) is a suitable comparator in the modelling exercise. Previous maintenance of slenderness ratio λ permits correct modelling of buckling as long as initial curvature is scaled. This will occur automatically if out of straightness is the result of a bow induced by a thermal gradient.

A NEW MODEL FIRE CURVE

A thermal onslaught must be provided, which will produce the normalised temperature distribution criterion detailed above. The thermal transmission process includes conduction of heat through the extent of the specimen thickness, prompted by a thermal flux incident on to the specimen surface.

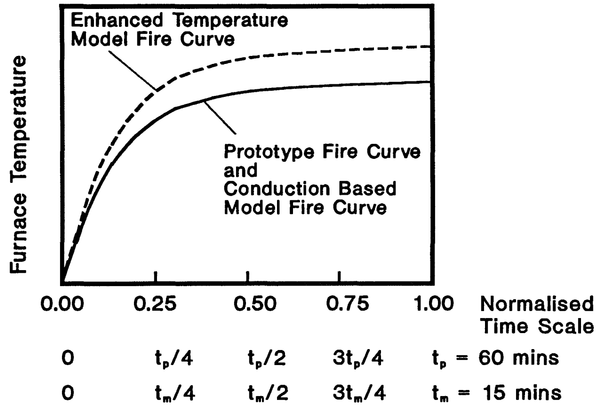

FIGURE 2: Normalised Fire Curves

The Conduction Process

The form of the internal curvilinear temperature distribution is prompted by the transient thermal diffusion equation:

$$\frac{dT}{dt} = \frac{k}{\rho C_p}\left(\frac{d^2T}{dx^2}\right) \tag{3}$$

Response is controlled by the non-dimensional Fourier number ($\gamma.\Delta t/\Delta x^2$). Given that the diffusivity $\gamma = k/\rho C_p$ refers to consistent material properties similarity is controlled by the ratio $\Delta t/\Delta x^2$. This infers *a scale-squared time scale rule*, noted also by other authors. With reference to a half scale model a quarter time scale is required, that is a prototype fire test lasting one hour will be replicated using a model fire curve lasting 15 minutes. The relationship between fire curves can be mapped on to a normalised form, shown in Figure 2. Both curves are represented by a single heavy line, using the same temperature axis, but with individual scaled time axes.

It is recognised that this treatment is based on a pure conduction model. Although consistency of diffusion properties between model and prototype are maintained, size effects associated with moisture movement and phase changes, may distort the base reasoning.

Boundary Requirements

The thermal diffusion process is driven by an net incident flux boundary condition, whose magnitude is defined by the instantaneous surface temperature gradient ($q_n = k\delta T/\delta x$). Inspection of the basic similarity criterion, defined by the normalised temperature distributions of Figure 1, leads to the final criterion for thermal scale modelling - the *inverse* *scale* or *double the flux* rule. In a half scale model a net incident flux of double the prototype magnitude is required to produce the required temperature distribution in the model.

One of the weaknesses of the standard fire test is that the control boundary definition is remote from the surface of the specimen and furthermore, control of the thermal severity of the furnace environment is itself indirect, by means of temperature rather than by means of heat flux. Thus, manipulation of a test furnace environment to produce appropriate flux on a model specimen is not a trivial exercise. In this methodology it is suggested that the required increase in heat flux be quantitatively obtained by increasing the furnace temperature. Provided that the furnace operation is well known and can be defined in terms of controlling parameters, a new enhanced model fire test temperature-time curve may be evaluated. The ensuing enhanced temperature curve mapped on to the previously discussed normalised time axis is shown in Figure 2. In an alternative approach, a total furnace flux-time curve may be quantified and employed to control a model fire test in a test furnace by means of flux measurement instrumentation.

The Surface Heat Transfer Process

The net incident heat flux q_n transmitted through the specimen boundary interface can be quantified as:

$$q_n = h_c(T_f - T_w) + a_w(\sigma \epsilon_f T_f^4) - (\sigma \epsilon_w T_w^4) \qquad (4)$$

The first term of the equation represents convective heat transfer between furnaces gases T_f and wall specimen T_w. Its magnitude depends on the configuration of the test furnace and, although significant during the initial stages of a fire test, the radiative terms controlled by T_f^4 and T_w^4 tend to dominate furnace operation.

Furnace radiative impact is described by the term $(\sigma\epsilon T_f^4)$, the emissivity ϵ describing the efficiency of the furnace with respect to the measured gas temperature T_f. The resulting heat flux on the wall specimen boundary is attenuated by the surface absorptivity a_w (0-1.0) and reduced considerably by (re)radiation from the specimen surface $(\sigma\epsilon_w T_w^4)$. Invoking the inverse scale factor rule for scale modelling, reasoned above, the general relationship of net incident flux between model and prototype may be written as:

$$h_c(T_{f,m} - T_{w,m}) + \sigma(\epsilon_f T_{f,m}^4 - \epsilon_w T_{w,m}^4) = \frac{1}{s}[h_c(T_{f,p} - T_{w,p}) + \sigma(\epsilon_f T_{f,p}^4 - \epsilon_w T_{w,p}^4)] \qquad (5)$$

Radiative terms have been grouped and a_w incorporated into ϵ_f. For a half scale model $1/s = 2$ (double the flux).

Considering that the first dynamic similarity condition requires that $T_{w,m} = T_{w,p}$, (Figure 1) and assuming that h_c, ϵ_w and ϵ_f may be defined over the duration of the fire test, Eqn. (5) may be used to determine the model fire curve $T_{f,m}$ from the standard prototype fire time-temperature curve $T_{f,p}$. Unfortunately $T_{f,m}$ cannot be explicitly presented as the subject of the equation. In practice, a system of trial and error may be employed to determine $T_{f,m}$ at suitable time intervals, by iteration of Eqn (5).

Simpler explicit solutions may be obtained by considering either purely convective or purely radiative furnace operation models. A convective model [5] is not practical due to its muted importance in test furnaces. However, in many cases, a purely radiative mode [6] can give a pragmatically workable solution. The dependence of radiative flux magnitudes on T_f^4 results in a not excessive furnace temperature requirement (ie. factoring up by approx. $\sqrt[4]{2}$ in a half scale model). In particular, if furnace operation is more simply expressed in terms of a global resultant emissivity ($\epsilon_f = \epsilon_w = \epsilon$), Eqn (5) may be reduced to a form, which is dependent only on the scale factor (s) and the prototype test data, dependence on the emissivity (ϵ) being removed. The simple radiative model fire curve expression then reduces as follows:

$$T_{f,m} = \sqrt[4]{T_{w,p}^4 + \frac{1}{s}\left(T_{f,p}^4 - T_{w,p}^4\right)} \qquad (6)$$

which simplifies further, for half scale when $1/s = 2$.

PRACTICALITIES OF FURNACE MODEL FIRE TESTING

Definition of thermal impact on even a plane specimen and quantification of incident flux magnitudes by means of expressions such as Eqn (4), using the furnace gas temperature as a comparator is fraught with difficulty. However, quantification in these terms for most research laboratory furnaces is achievable and many organisations have thorough knowledge of their furnace response through attempting to calibrate computer simulations with fire test results. It must be stressed that the methodology is considered applicable in parametric studies on model structural forms, to be carried out in the same furnace and that it is recommended that a single test be carried out on a suitable portion of prototype, to verify future model thermal data.

In the research study supporting these proposals, the need for the quantification of furnace fire severity in terms of total furnace flux-time curves became apparent. This prompts the response that perhaps the most satisfactory way to provide the incident flux requirements of a model fire test is to define the model fire test as a gross furnace flux-time curve. It is however noted that the model fire curve is defined in net incident flux terms and the furnace is at best controlled in gross flux terms. The methodology is thus sensitive to wall temperature and dependent on specimen material properties. Steel specimens for example will attain much lower surface temperatures than say concrete in the same fire test. This means that a different model test fire curve would be required for each which would introduce problems when dealing with composite or non uniform construction.

Scaling of surface effects is also necessary on the unexposed (ambient) face. This would be difficult to achieve except through say forced convection but its role in tests to date has been minor and has not been examined in detail.

RESULTS FROM TEST PROGRAMMES

1. Brickwork and Concrete Walls

A recent project [9] examined the model test methodology in relation to the free bowing of brickwork strips. Some 30 fire tests were performed on small scale samples of concrete brickwork and plain concrete to study the development of thermal distributions through the thickness. Prototype results on samples 100mm thick were compared with models 70mm and 50mm thick, at $1/\sqrt{2}$ and 1/2 scale. In addition some 12 fire tests were conducted on concrete brickwork panels, 2½ bricks wide. Prototypes were nominally 100mm thick x 1500mm high with models 50mm thick x 750mm high. The furnaces used for model and prototype tests were clean burn propane fired with high insulation ceramic fibre linings. Enhanced temperature model fire curves were generated by Eqn (6), radiation only mode, and typical fire curves are shown in Figure 3. The prototype test lasted 1 hour (60 mins) with the $1/\sqrt{2}$ scale test lasting 30 mins (1/2 time) and the 1/2 scale model fire test lasting 15 minutes (1/4 time). Thermal distributions are illustrated in Figures 4 and 5 for typical ($1/\sqrt{2}$) and (1/2) scale tests. Thermocouples were positioned at 5 points through the sample thickness and on each surface. Inspections shows there to be good agreement between model and prototype temperatures. There are some variations in the region of the moisture lag phase around 100°C but these are not particularly crucial, being most significant in the sections closer to the external face. Good similarity of temperatures close to the fire exposed face are achievable and these regions are most crucial to the onset of failure in reinforced sections. In the case of the free bowing of a brick wall overall temperature gradients through the thickness are the drivers of thermo-structural response. Figure 6 gives a comparison of bowing displacements between a half scale model and prototype and shows reasonable agreement in normalised displacement magnitudes.

2. Reinforced Concrete Slabs

Another application of the methodology was the fire testing of half scale reinforced concrete slab strips [8]. In this case the objective of the project was to use fire tests on half scale models to examine the utility of a quasi-plastic analysis for the determination of the fire resistance of loaded continuous reinforced concrete slabs. Time response and heating rates were significant and the model test methodology was crucial in being able to produce in the 70mm thick model specimen temperature distributions, which would be normally expected in actual slabs 140mm thick. This requirement was achieved. The outputs of the study are summarised in the table below, which gives a comparison between analysis and test fire resistance times for simply supported and continuous beams. Half scale model fire resistance times were in the order of 30 minutes relating to prototype fire resistances of some 2 hours, but notably, load ratios were quite high.

This test programme puts model fire testing in perspective. Although in some applications the test programme will be used as the major indicator of the assessment of structural behaviour, in other cases, it is only necessary to produce a fire test response, which is globally typical of generalised behaviour. The model test method gains in terms of scale and cost. Notably, the above test programme was able to simulate physically the performance of a continuous 3 span floor slab 140mm thick, 3.600m internal span, using a self reacting load test rig, suspended over a small floor furnace of maximum significant dimension only 1.600m (1.8m span).

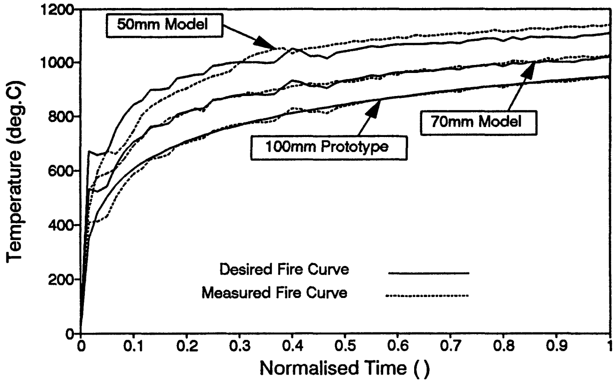

FIGURE 3: Experimental Fire Time Temperature Curves

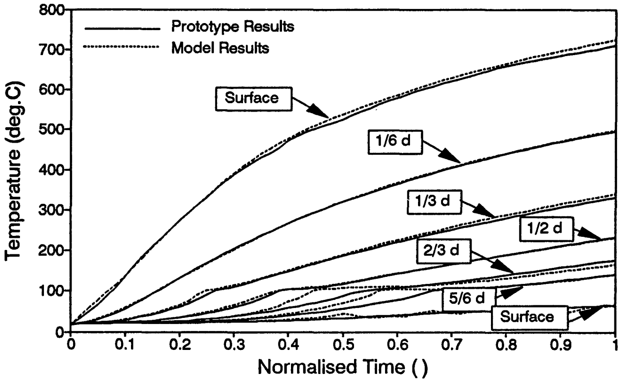

FIGURE 4: Model and Prototype Temperature Distributions at $1/\sqrt{2}$ Scale

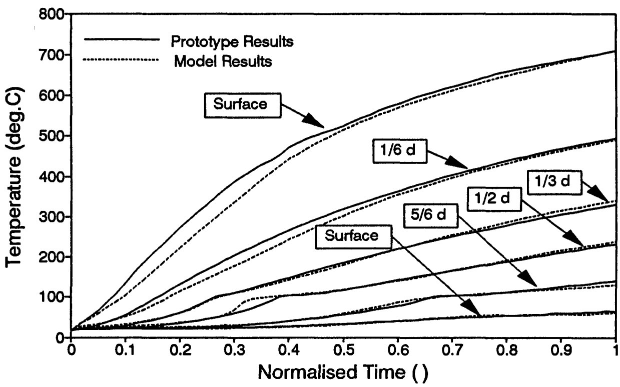

FIGURE 5: Model and Prototype Temperature Distributions at 1/2 Scale

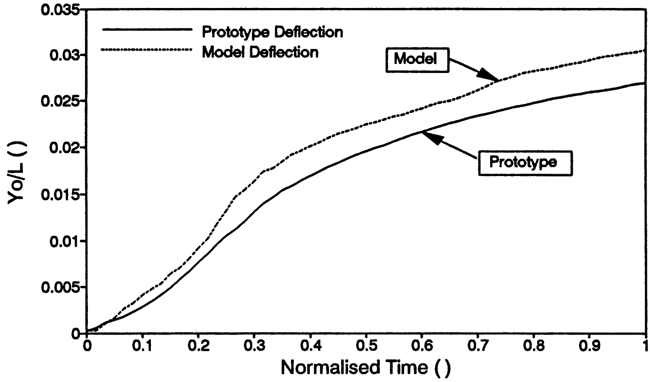

FIGURE 6: Model and Prototype Normalised Displacements

Arrangement	Load	Load Ratio	FR-Time Analysis	FR-Time Test
Simple Beam C1	4.0 kN	77%	24 min	25 min
Simple Beam D1	4.5 kN	86%	22 min	24 min
Continuous Beam C2	8.0 kN	61%	> 30 min	> 30 min
Continuous Beam D2	10.5 kN	80%	27 min	26 min

TABLE 1: Models: Test and Analysis Fire Resistance (FR) Times

3. Steel Columns

A 5 year test programme [9] is in progress, examining the effect of fire related temperatures on the behaviour of steel columns acting within frames, with particular emphasis on the effect of axial and rotational restraint. This research takes the form of physical testing parametric studies, whose data output is being used in a comparison study with computer models. All general physical modelling considerations described earlier are relevant, the crucial modelling factors being quantification of geometrical non-linearity and the relationship of stresses to temperature dependent yield criteria. As time effects are not considered significant a model fire curve is not required, so a simple steel temperature-time ramp is being applied to

CONCLUSIONS AND RECOMMENDATIONS

A model test methodology has been developed for application to the fire testing of structural systems, particularly at half scale. The model fire test has the potential to produce scaled thermo-structural displacements or structural failure conditions at scaled fire resistance periods.

Rules for the formulation of new model fire test are defined. An initial normalised temperature distribution condition requires the imposition of a double incident heat flux and quarter time scale rules for a half scale model fire test. The increased flux requirement can be accommodated by an enhanced temperature axis.

The application to several specific cases have been examined and possible limitations explored. It is recommended that the methodology is suitable for application as a research tool to facilitate parametric studies for the examination of generalised behaviour or the validation of computer models or for indicative testing.

Total flux measurement could provide a more satisfactory control of the required thermal environment in model fire tests.

REFERENCES

1. Quintiere, J.G., "Scaling Applications in Fire Research", Fire Technology, Vol.15, pp.3-29, 1989.

2. Sahota, M.S., Pagni, P.J., "Temperature Fields in Structural Elements Subject to Fires", Transactions of the ASME, Journal of Heat Transfer, pp.598-604, 1975.

3. McGuire, J.H., Stanzak, W.W. & Law, M., "The Scaling of Fire Resistance Problems", Fire Technology, Vol.11, No.3, pp.191-205, 1975.

4. Ng, Ah Book, Mirza, M. Saeed, Lie, T.T., "Response of Direct Models of Reinforced Concrete Columns Subjected to Fire", A.C.I. Structural Journal, Vol.87, No.3, pp.313-325, 1990.

5. O'Connor, D.J. and Silcock, G.W.H., "A Strategy for the Fire Testing of Reduced Scale Structural Models", Fire Technology, pp.48-69, Feb.1992.

6. O'Connor, D.J. and Silcock, G.W.H. and Morris, B., "Furnace Heat Transfer Processes Applied to a Strategy for the Fire Testing of Reduced Scale Models", subject to final approval for publication in Fire Safety Journal,

7. O'Connor, D.J., Silcock, G.W.H. and Morris, B., "An Investigation of Scale Modelling of Thermo-structural Performance of Compartment Walls in Standard Fire Tests", Proceedings of the British Masonry Society, Vol.2, No.7, pp.402-406, 1996.

8. O'Connor, D.J., McAllister, B. Munro,J. & Bennett, H.R., "Determination of the Fire Endurance Of Model Concrete Slabs Using A Plastic Analysis Methodology", Structural Engineer, Vol.74, No.19, pp.325-330, Oct.1995.

9. O'Connor, D.J., Silcock, G.W.H. and Shields, T.J. "Performance in Fire of Restrained Columns in Steel Framed Construction", EPSRC Research Grant GR/K 59828, Feb 1996.

10. Ali, F.A., Simms, I.W., O'Connor, D.J., "Behaviour of Axially Restrained Steel Columns During Fire", To be presented at the Fifth International Symposium of IAFSS, Melbourne, 1997.