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Finite element numerical evaluation of elliptical hollow section steel columns in fire

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ABSTRACT

To complement previous experimental studies on the performance of unprotected Elliptical Hollow Section (EHS) steel columns, under the hydrocarbon fire curve, a numerical analysis has been performed and outlined in this paper. A three-dimensional Finite Element Method (FEM) model has been developed and calibrated against 12 experiments, comprising of six unrestrained and six axially restrained EHS columns of two slenderness, $\lambda_z=40.1$ and $\lambda_z=50.8$. The EHS temperature profiles and axial displacements, measured under three different loading levels, ($\alpha_L=0.3$, 0.45 and 0.6) were utilised in the calibration process. The mechanical and thermal properties for carbon steel at elevated temperatures, detailed in the Eurocode standard EC3 Part 1–2, design of steel structures [1] have been applied. Axial displacement charts illustrate that a close agreement between the FEM model and the experiment results was achieved, while highlighting how critical the thermal expansion coefficient and geometric imperfection was during the calibration process. Ultimately, the paper will detail appropriate recommendations for the thermal analysis of unfilled Elliptical Hollow Section steel columns, of steel grade S355J2H, and provide the platform for comprehensive parametric fire investigations to commence.

1. Introduction

The Elliptical Hollow Section (EHS) is the newest member of the Steel Hollow Section (SHS) family, and has been the focus of numerous studies over the last number years. This new hollow section type provides an exciting alternative to the rectangular and circular counterparts, for structural design engineers and architects. The continuously changing outside curvature not only provides elegant lines for aesthetic appeal, but numerous moments of inertia, that can be used to enhance and pioneer new structural designs.

Until recently, research into this new structural shape have been limited to a few studies in the 19 60s and early 1970s, which observed the buckling behaviour of oval cylindrical shells, manufactured from polyester film. These investigations included stability under compression [2], and a combination of bending moments under axial force [3]. The downside to these studies realised that their plastic resistance could not be achieved. It was recognised that to enhance the structural design guidance for this new section, a number of in-depth investigations would be required. One of the first comprehensive studies was the cross section classification by Gardner and Chan [4], which grouped each EHS cross section into four classes. Grouping into these classes, identified the resistance and rotation capacity limits of the cross section, before failure occurred by local buckling. This study concluded that the class limits for Circular Hollow Sections (CHS) were deemed applicable, if an equivalent diameter for the EHS was obtained. Further studies in this comprehensive experimental programme by Chan and Gardner, explored the flexural buckling [5], bending strength [6] and compressive resistance [7] response of member length EHS columns. The elastic buckling of Elliptical Hollow Sections in compression was also investigated by Ruiz-Teran and Gardner [8] and analysed by Silvestre [9].

Filling the Elliptical Hollow Section void with concrete is a practice widely used in Circular (CHS) and Rectangular Hollow Sections (RHS), this provides additional structural qualities to the section; these qualities include increased stiffness, compressive strength and additional fire resistance. Yang et al. [10] investigated the structural properties of concrete-filled elliptical hollow sections (CFEHS) while suggesting a proposed design formula for member design. Zhao and Packer [11] also investigated concrete filled EHS stub columns. This investigation verified the suitability of circular equivalent diameters, but in addition proposed effective RHS width and depth dimensions, as local buckling observations resembled plate buckling rather than cylindrical shell buckling.

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Nomenclature

Δl	vertical axial displacement
Δt	time step increment
$\Delta\theta_{a,t}$	increase of steel temperature
A	cross-sectional area of column steel
A_m	unit surface area exposed to fire
$C_{a,t}$	dpecific heat capacity at temperature
E_a	modulus of elasticity at ambient temperature
f_y	yield strength
H	outside dimension of EHS on minor axis
$\dot{h}_{\text{net}}$	net heat flux
$\dot{h}_{\text{net},c}$	convective net heat flux
$\dot{h}_{\text{net},r}$	radiative net heat flux
h_c	convection heat transfer coefficient
h_{com}	combined heat transfer coefficient
h_r	radiative heat transfer coefficient
I	second moment of area
L	original column length
L_e	effective length
P_a	load applied to column
P_{cr}	critical buckling load of column
q_c	convective heat flux per unit area
q_r	radiative heat flux per unit area
q_{tot}	total (Convection and radiation) heat flux per unit area
r	radius of gyration
T	thickness of EHS wall
T_F	furnace temperatures (FEM)
T_S	steel temperatures (FEM)
u	free thermal expansion
V	section volume per unit length
ν	Poisson's ratio
x	geometric imperfection
α	thermal expansion coefficient
α_c	convection coefficient
α_L	axial load ratio
ε	strain
ε_m	steel member surface emissivity
ε_f	furnace surface emissivity
Θ_f	furnace temperatures
$\Theta_{f,t}$	furnace gas temperature with respect to time
Θ_g	gas temperatures
Θ_m	steel member surface temperature
$\Theta_{m,t}$	steel member surface temperature with respect to time
Θ_r	radiation induced temperatures
λ_B	Euler buckling value
λ_z	slenderness about the z-axis
ρ_a	density of carbon steel at ambient temperature
σ	Stefan Boltzmann constant
σ_{cr}	elastic critical buckling stress
Φ	radiation configuration factor

Only a few viable Finite Element (FE) studies on Elliptical Hollow Sections have been carried out to date, the most significant performed by Zhu and Wilkinson [12]. They investigated the local buckling behaviour of the EHS, while verifying that the equivalent CHS diameters proposed by Gardner and Chan [13] was a viable approach to adopt. Espinos et al. [14] produced a Finite Element model to understand the behaviour of CFEHS, with proposed design guidance. The FEM model used in Espinos's investigation was calibrated with historical temperature profiles from concrete-filled circular hollow sections (CFCHS). This investigation however, will use the experimental data obtained from the first ever studies into the fire resistance of unrestrained [15] and axially restrained [16] unfilled EHS steel columns performed by Scullion et al., to calibrate the FEM model.

2. The experimental investigation

A hydrocarbon fire based experimental investigation, comprising of 12 unfilled pin-ended Elliptical Hollow Section steel columns, was conducted at the FireSERT facilities of the University of Ulster. The two part experimental programme tested two different section sizes, $250\times125\times8.0$ mm and $200\times100\times8.0$ mm with slenderness λ_z=40.1 and λ_z=50.8, namely EHS-A and EHS-B, respectively. The first stage tested six columns, three of each slenderness, unrestrained and under three different loading levels (α_L=0.3, 0.45, 0.6). These first tests demonstrated the unique local and global buckling modes of the EHS columns under compressive loads, full details of the results are available in Scullion et al. [15]. The second stage of the experimental program applied axial restraint to the EHS columns thermal expansion. As columns are rarely used in isolation, the application of this axial restraint represents a more realistic condition of column boundary constraints, found in construction. This study illustrated the additional axial forces that are present when restraint is applied and demonstrated the accelerated failure rates of the EHS columns. Full listings of the experimental results and comparisons with the unrestrained EHS columns are documented in Scullion et al. [16].

3. Finite element analysis

Fire testing of structural elements is expensive, through an accumulation of running costs and test specimen expenditure. As test specimens have only a one test life time, the advantages of using Finite Element (FE) models become even more beneficial. The Finite Element Method (FEM) is a numerical modelling technique that finds approximate solutions for partial and integral equations. With the advancements in computer technology both in FE software and computing processing speeds, the ability for solving complex elasticity and structural analysis problems has become extremely applicable. However, an FEM model for thermal analysis can only be successful and credible, if the correct input parameters and time–temperature varying values for material properties are correctly detailed. In the absence of tensile coupon testing or experimental data, the most reliable source to date for obtaining thermal and mechanical properties for structural carbon steel is from the structural Eurocode (EC) publications. This investigation will use these EC material parameters to develop and calibrate an FE model, detailing the unfilled Elliptical Hollow Section steel column under various loading and restraint levels, subjected to fire.

The Finite Element Analysis (FEA) software used for this verification process was the software package TNO-DIANA Version 9.4, with model geometry and mesh created using the windows based graphical user interface (GUI) Midas FX+Version 3.0.0. A three-dimensional numerical model was created, utilising the staggered heat flow-stress analysis modules of DIANA. The model first demonstrated and validated the maximum compressive capacity resistance of the columns at room temperatures, before a structural thermal analysis commenced. The requirement for a heat flow-stress working domain environment determined the Finite Element (FE) selection.