Fire Safety Journal 71 (2015) 150–161

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Effect of transverse reinforcement spacing on fire resistance of high strength concrete columns

Szymon Seręga *

Cracow University of Technology, ul. Warszawska 24, 31-155 Kraków, Poland

ARTICLE INFO

Article history:
Received 3 April 2014
Received in revised form
2 September 2014
Accepted 23 November 2014
Available online 10 December 2014

Keywords:
HSC columns
Fire temperatures
Fire resistance
Transverse reinforcement spacing

ABSTRACT

The confinement effect due to the congested transverse reinforcement is a very important feature for reinforced concrete columns subjected to accidental load conditions. The influence of transverse reinforcement spacings on load bearing capacity of high strength concrete (HSC) columns at ambient temperature has been the subject of many research projects, both experimental and theoretical. However, at high temperature the results of research into this subject are scarce and do not provide unambiguous evidence as to the effect of spacing of transverse reinforcement on fire load capacity and fire resistance.

The first part of this paper presents an experimental study of the influence of transverse reinforcement spacing on fire resistance of axially loaded, HSC columns with circular cross-section. The results of full-scale tests indicate that columns with spacing of ties recommended by the code provisions for design of concrete structures could suffer a premature failure as a consequence of inelastic buckling of main reinforcing bars between adjacent ties.

The next part of the paper concerns the supplementary numerical analysis of tested columns. The columns were modelled in axisymmetry with embedded reinforcement. The applied material model took into account the influence of transient temperature on mechanical properties of concrete and steel. The effect of cracking, development of transient creep strains and plastic strains for concrete were also included in the analysis. The inelastic buckling of main reinforcement was modelled using average stress–strain relationships for steel in compression. The comparison of numerical simulations and experiments shows reasonable agreement. The assessment of failure modes using the numerical simulation is also presented in the paper. The results of calculations indicate that during the whole heating period high thermal gradients generated tensile stresses in the plane of cross-section of the columns. Due to this fact the confinement effect was not observed for the columns with congested spacing of transverse reinforcement.

1. Introduction

Reinforced concrete columns constitute one of the most important parts of structural systems in multi-storey buildings. In such type of structures columns are usually subjected to high compressive forces and relatively small bending moments. In this case high strength concrete (HSC), i.e. concrete with class higher than C50/60 [1,2] is becoming more frequently used as construction material for columns. Compressed reinforced members made of HSC, however, exhibit a lack of ductility after the ultimate load is reached [3], which makes the structure less capable of redistributing internal forces. The effect of brittle failure of HSC columns is especially dangerous for structures exposed to accidental severe actions such as explosions or earthquakes. The appropriate ductility of HSC columns is usually achieved by fulfilling the structural requirements for critical regions of elements concerning minimum main reinforcement ratio, reduced spacings and proper arrangement of transverse reinforcement [4,5].

The influence of transverse reinforcement on the load bearing capacity and post-critical behaviour of reinforced concrete columns at ambient temperature was the subject of many research projects – see for example references [6–13]. Experiments conducted at normal temperature show that due to the confinement effect there is noticeable increase in load bearing capacity for axially loaded columns with congested spacing of transverse reinforcement. Moreover, the closer the transverse reinforcement spacing the more ductile behaviour of a column is observed. The positive influence of transverse reinforcement on the load bearing capacity of reinforced concrete columns at room temperature raises a question whether an analogous phenomenon would be

* Fax: +48 126320966.
E-mail address: sserega@pk.edu.pl

http://dx.doi.org/10.1016/j.firesaf.2014.11.017

Nomenclature

c_p	specific heat
e_a	imperfection eccentricity of columns
e_{imp}	initial imperfection of steel bars
E_{cm}	elastic modulus of concrete
k_{c1}	transient creep coefficient
f_c	uniaxial compressive strength of concrete
f_t	uniaxial tensile strength of concrete
N_{Rfi}	fire load capacity
t	time
t_{fi}	fire resistance
s_w	ties spacing
α	coefficient of thermal expansion
δ_{ij}	Kroneker's delta
ε_{ij}	total strain tensor
ε_{ij}^{th}	free thermal strain tensor
ε_{ij}^{el}	elastic strain tensor
ε_{ij}^{pl}	plastic strain tensor
ε_{ij}^{tr}	transient creep strain tensor
ϕ	diameter of main reinforcing bars
λ_c	heat conductivity
ν	Poisson's ratio
ν_c	material constant
θ	temperature
ρ_c	density
σ_{ij}	stress tensor
σ_{rr}	stress in radial direction
$\sigma_{\varphi\varphi}$	stress in circumferential direction
σ_{zz}	stress in vertical direction
σ_s	stress in steel bars
∇	nabla operator

observed in fire conditions. However, an answer to this question is not obvious.

Due to the low thermal conductivity of concrete, the high temperature during fire generates heterogeneous temperature fields associated with high thermal gradients. The experiments described in [14] conducted on unloaded hardened cement paste cylinders show that during rapid heating tensile stresses generated by thermal gradients are high enough for possible cracks to occur in the radial and tangential directions. This means that in the case of axially loaded columns with tightly arranged stirrups rapid heating may eliminate the positive effect of confinement in the core of a concrete column. Hence, increasing the transverse reinforcement ratio, which increases the load capacity of axially loaded columns at room temperature, may not lead to an increase of the fire load capacity (N_{Rfi}) and fire resistance (t_{fi}).

Another important effect that should be considered in the design of compressed reinforced concrete members is inelastic buckling of main reinforcing bars between adjacent ties. Design codes usually assume that inelastic buckling of this reinforcement does not take place when the bar slenderness ratio (s_w/ϕ) is limited to the following values: 20, [15] 16, [4] 10 or 15, [16] where s_w is transverse reinforcement spacing and ϕ is the diameter of main reinforcing bars. According to these recommendations the spacing of lateral reinforcement constitutes sufficient protection against buckling of bars for service loads. However, if the load reaches the ultimate level the basic spacing of ties may be insufficient [17,18]. When the column is subjected to fire, the concrete cover is seriously weakened and the compressive stress in the main reinforcement increases. In this case the main reinforcing bars are prone to inelastic buckling. The reduced slenderness ratio s_w/ϕ could limit this phenomenon and increase the fire resistance of compressed concrete elements. The first suggestions that insufficient spacing and detailing of transverse reinforcement may lead to premature failure of HSC columns were given in references [19,20]. The authors of [20] also stated that reduction of stirrups spacing to 0.75 of its basic value as well as proper anchorage of stirrups ends in the column core reduce spalling and improve the fire performance and fire resistance of HSC columns.

Until now experimental research into the influence of transverse reinforcement spacing on fire resistance of HSC columns has been scarce. Figs. 1 and 2 present the available experimental results of this effect for columns with square and circular cross-section, according to the experiments reported in [21–23]. Details concerning these experimental campaigns are summarised in Tables 1 2. It is worth noting that only in the experiments [21,22] the effect of different spacings of transverse reinforcement was explicitly investigated. The spacings of ties in tests [23] were

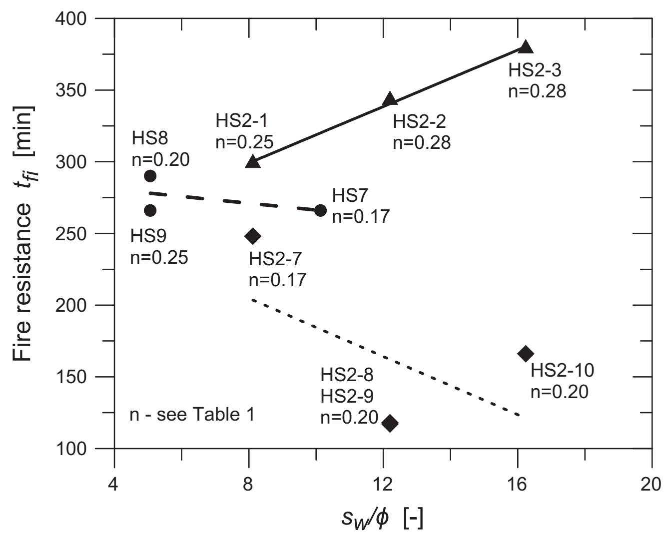

Fig. 1. Effect of main reinforcement slenderness ratio s_w/ϕ on fire resistance of square cross-section columns [21,22].

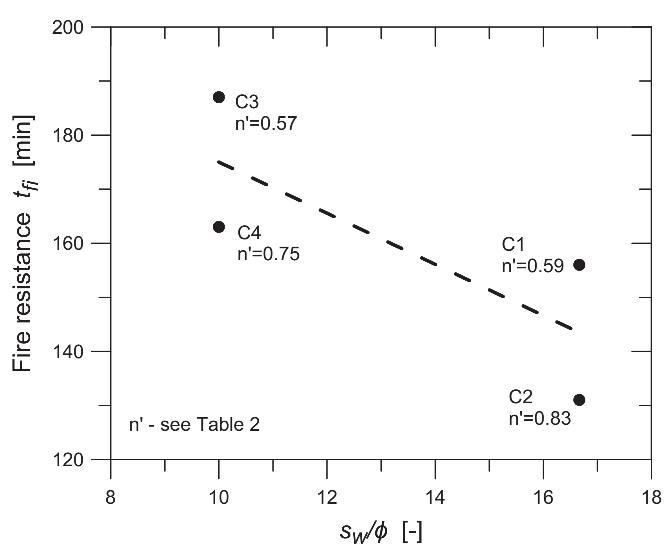

Fig. 2. Effect of main reinforcement slenderness ratio s_w/ϕ on fire resistance of circular cross-section columns [23].