FIRE RESISTANCE OF INTERNALLY OR EXTERNALLY CONFINED REINFORCED CONCRETE COLUMNS

Hanaa I. El-Sayad[1] And Aiman A. Shaheen[2]

ABSTRACT

The aim of this investigation is firstly to evaluate the different methods used for confining the reinforced concrete (R.C) columns either internally or externally. Secondly, the effect of overheating on the performance of confining methods is studied using the computer program "ANSYS 5.4". Beside the traditional transverse steel ties, the internal confinement was satisfied by steel fibers or a cage of expanded metal mesh inside the ties, while external confinement was achieved by wrapping the studied columns with ferrocement layers or GFRP sheets. Six R. C columns were prepared, namely, the control column reinforced traditionally with transverse ties only, two columns containing 1% and 2% steel fibers, one column reinforced additionally with a cage of expanded metal mesh, two columns wrapped with either ferrocement laminates or glass fiber reinforced plastics (GFRP). The columns were tested under axial loads to evaluate the effect of the different confining methods on the ultimate capacity and ductility. It was found that adding 2% steel fibers or reinforcing the column with a cage of expanded metal mesh inside the ties gave almost similar results (26% increase in the ultimate capacity compared with that of the control column). Despite that the ultimate capacity of the column wrapped with GFRP was the highest among the studied columns (37% increase in the ultimate capacity), its ductility was the lowest. The parametric study using ANSYS 5.4 showed that the R.C columns containing steel fibers were less affected by fire than the other columns. It was also found that the ultimate capacity of R.C columns wrapped with GFRP was reduced by fire to a high degree (approximately 53% reduction in the ultimate capacity).

ملخص البحث:

يقدم البحث دراسة عملية تهدف إلى بحث تأثير استخدام أساليب ومواد جديدة لتقوية الأعمدة الخرسانية المسلحة بغرض رفع مقاومتها القصوى وتحسين ممطوليتها، كما يحتوى البحث على دراسة نظرية باستخدام برنامج الحاسب الآلى 5.4 ANSYS لــبحث تأثير الحريق على هذه الأعمدة بغرض معرفة أى المواد والأساليب الجديدة أكثر تأثرا بالحريق. تم اختــبار ستة أعمدة خرسانية معمليا تحت حمل محورى، الأول مسلح بحديد طولى وكانات عرضية أما الخمسة أعمدة الــباقية فهى بالإضافة للتسليح المذكور تحتوى على الترتيب: ألياف صلب بنسبة ١%، ٢% ، الاحاطة الخارجية بطبقة مــن صــلب الشــبك الممدد مغموسة فى المونة (الفيروسمنت)، التسليح العرضى بشبك الصلب الممدد داخل الكانات العرضية وأخيرا الاحاطة الخارجية برقائق الألياف الزجاجية GFRP. أثبتت نتائج الاختبارات المعملية زيادة المقاومة القصـــوى والممطولية للأعمدة المقواة بالأساليب والمواد الجديدة بدرجات متفاوتة مقارنة بالعينة المرجعية، فعلى الرغم من أن المقاومة القصوى للعمود الذى تمت تقويته باستخدام GFRP كانت أعلى من باقى الأعمدة الا أن ممطوليته كانت منخفضة بينما أظهر العمود المحتوى على ألياف من الصلب بنسبة ٢% وكذلك العمود المسلح بشبك ممدد بنسبة ٢, ٢ % زيــادة ملموســة فى مقاومــتهما وممطوليتهما. أظهرت مقارنة نتائج التحليل العددى بالنتائج المعملية توافقا جيدا، وبالتالى امتد التحليل العددى ليشمل تأثير الحريق على نفس نماذج الأعمدة المدروسة معمليا. أظهرت النتائج أنه بالرغم مــن كفاءة GFRP المسجلة معمليا فى رفع المقاومة القصوى للأعمدة المدعمة بتلك المواد إلا أنها أكثر المواد تأثرا بالحريق بصورة كبيرة تليها الأعمدة المقواة بالفيروسمنت، كما وجد أن أقل الأعمدة تأثرا بالحريق تلك التى تحتوى على ألياف من الصلب يليها التى تحتوى على شبك ممدد كتسليح عرضى ثم الأعمدة التقليدية المسلحة بالكانات.

[1] Associate Professor, Civil Engineering Department, Banha University
[2] Associate Professor, Civil Engineering Department, Cairo University, Fayoum Branch

INTRODUCTION

The key factors for resistance of reinforced concrete (R.C.) columns to gravity and lateral loads are the ultimate capacity and ductility of such columns. Satisfying these key factors were normally achieved by proper internal confinement of R.C. columns using the traditional tie "transverse" reinforcement. Recently, internal confinement using short steel fibers or a cage of wire mesh [1 and 2] and external confinement using wire mesh imbedded in mortar (ferrocement) or wraps of advanced composite sheets [3 and 4] greatly improved the performance of R.C columns, in buildings under gravity or seismic loads. Harajli and Rteil [1] reported that internal confinement using steel fibers in the columns improved performance similar to external confinement with carbon fiber sheets. Razvi and Saatcioglu [2], Furlong et al. [5], Mau et al. [6] and Aikhionbare and Tabsh [7] found that the columns internally confined by welded wire fabric inside or outside the transverse ties showed a significant improvement in strength and ductility compared with those designed according to ACI Building Code [8] with closely spaced ties and longitudinal reinforcement only. Saatcioglu and Grira [9] found that welded grids offer an economic alternative to conventional ties with reduced construction time, especially for earthquake resistant construction where the tie details may be prohibitively complex.

Fahmy et al [3] studied the external wrapping of ferrocement laminates in repairing of reinforced concrete. It was found that the results of all repaired specimens demonstrated better behavior and load carrying capacity compared to their original behavior. Saadatmanesh [4] found that the stress-strain models for concrete confined with composite straps indicate significant increases in compressive strength and strain at failure when compared with the stress-strain behavior of unconfined concrete. Naguib and Mirmiran [10] studied the effect of lateral confinement on the behavior of the concrete columns. Harajli and Rteil [1] studied the seismic performance of concrete columns reinforced with ordinary transverse steel and those confined externally with carbon fiber-reinforced polymer (CFRP) sheets. They found that confinement with the traditional transverse steel enhanced the seismic behavior and increased the energy absorption capacities of the columns but not as effective as confinement externally with CFRP.

The different techniques for internal or external confinement of R.C columns are affected by the elevated temperature to different degrees. Poon and Lam [11] reported that the addition of steel fibers (internal confinement) is more effective in minimizing the degradation of compressive strength for the concrete after exposure to the elevated temperatures compared to traditional reinforcement using transverse ties only. In addition, steel-fiber-reinforced concretes showed the highest energy absorption capacity after the high temperature exposure, although they suffered a quick loss of this capacity. Very little information is available for the effect of fire resistance on the wire mesh used as additional reinforcement in R. C. columns. However, it was reported that expanded metal reinforcement is better than welded wire reinforcement in fire resistance because the welds at the wire junctions melt at a temperature much smaller than that of steel wires [12]. ACI committee 549R-97 [12] stated the potentially poor fire resistance of ferrocement sections because of the inherent thinness of its structural forms and the abnormally low cover to the reinforcement. This is also applicable for the use of ferrocement as external confining tool. However, Naaman [13] proofed that ferrocement compares very favorably with GFRP when exposed to fire. Bisby et al. [14] reported that although the structural effectiveness of FRP materials can be maintained during fire, the fire behavior of FRP-wrapped columns can be dramatically improved by providing supplemental insulation for the FRP.

The objective of this research is firstly to evaluate the different methods used in confining square R.C columns, internally using expanded metal mesh or steel fibers, and externally using ferrocement laminates or GFRP, in improving the behavior of concrete columns compared with traditional reinforcement with transverse ties. Secondly, the effect of fire on the performance of the confining methods was conducted using the ready package computer program "ANSYS 5.4" [15].

EXPERIMENTAL PROGRAM

Test Specimens

Six R. C columns were prepared, namely, the control column reinforced traditionally with transverse ties only, two columns containing 1% and 2% steel fibers, one column reinforced additionally with a cage of expanded steel mesh (ESM), two columns wrapped with either ferrocement laminates or glass fiber reinforced plastics (GFRP) (see Figure 1). The columns were tested under axial loads concerning both strength and behavior to evaluate the effect of the different confining methods on the ultimate capacity and ductility. All columns were square in shape of height "h" = 100 cm and width "b" = 15 cm in order to achieve height to width ratio " h/b" = 6.6 to avoid buckling. The details of the tested specimens are listed in Table 1.

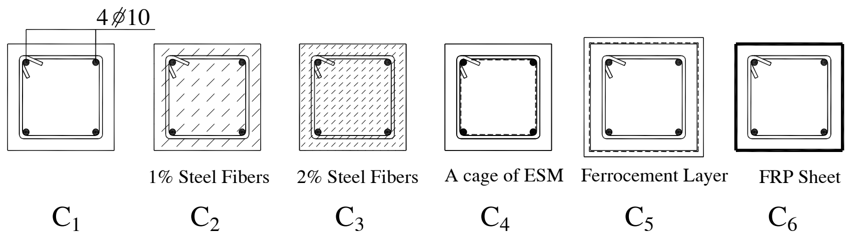
Materials and Mix Design

All concrete constituents used conformed to the relevant Egyptian Standard Specifications [16]. Sand and coarse aggregate (basalt) used were from a local pit. Two different size distributions of the basalt (14 and 5mm) were blended to obtain a uniform distribution. A superplasticizer based on polynaphthalene sulphate was used to improve the workability of the concrete mix. The actual cube compressive strengths for different specimens are given in Table 1. Table 2 provides the mix proportions. The steel used for the longitudinal reinforcement consisted of four 10 mm diameter high-grade steel (reinforcement ratio of 2.8%). The characteristic yield strength for steel used was 360 MPa. Column tie reinforcement was fabricated from 6 mm mild steel round bars, spaced at 20 cm, of characteristic yield strength 240 MPa. Hooked-end steel fibers of varying amounts, having yield strength of 400 MPa, were added in the mixes of columns with steel fibers. The aspect ratio of fibers was constant (L_f / D_f = 60 mm /1 mm = 60). Expanded steel mesh (ESM) used in this investigation was expanded metal lath conforming to ACI Committee 549, 1R-88 [17]. The mesh has a diamond shape of wire diameter equals 1.5 mm and the yield strength was considered 260 MPa [17]. For columns wrapped with GFRP, unidirectional E-glass composite (resin + fiber) tapes were used to wrap concrete columns. The properties of GFRP used were given by the manufacturer as follows; tensile strength =1103 MPa and modulus of elasticity = 48.2 Gpa.

Preparation of the Test Specimens

All the column specimens including the control specimen, C1, were reinforced with four corner bars of diameter 10 mm as longitudinal reinforcement and transverse ties of 6 mm diameter spaced at 20 cm along the column. Electrical strain gauges were fixed on the longitudinal reinforcement to record the strains. For column specimens, C2 and C3, hooked end steel fibers of volume content 1 and 2%, respectively, (see Table 1) were added during mixing of concrete. Column specimen, C4, was additionally reinforced by a cage of ESM of volume fraction, vf = 2.2% in the core inside the transverse ties. Column specimens, C5 and C6, were wrapped after casting and curing with one layer of ferrocement (a cage of ESM imbedded in mortar around the column) or a layer of GFRP imbedded in a resin, respectively.

The specimens were demolded after 24 hrs from casting, covered with wet burlap, and stored under laboratory conditions for 28 days. In addition, three 150-mm cubes were cast from each column mix and tested for compressive strength after a water-curing period of 28 days.



(a) Cross sections for studied columns

C5 C6

(b) Column specimens wrapped with ferrocement and GFRP

Figure 1 Preparation of the test specimens.

Table 1 Details of the Studied Column Specimens

Column Specimen Number	Concrete Strength MPa	Reinforcement		Confinement Method	
		Longitudinal	Transverse	Internal	External
C1	30	4 Φ 10	ϕ 6 @ 20 cm	--	--
C2	32	4 Φ 10	ϕ 6 @ 20 cm	1% steel fibers	--
C3	33	4 Φ 10	ϕ 6 @ 20 cm	2% steel fibers	--
C4	30	4 Φ 10	ϕ 6 @ 20 cm	Cage of ESM	--
C5	30	4 Φ 10	ϕ 6 @ 20 cm	--	One layer of ferrocement
C6	30	4 Φ 10	ϕ 6 @ 20 cm	--	One layer of GFRP

• Φ denotes high grade steel with 360 MPa, yield stress.

Table 2 Mix Proportions of Concrete Used in Preparation of the Columns

Characteristic Strength	Constituents and Mix proportions, kg/m^3				
	Cement	Sand	Crushed Basalt	Water	Superplasticizer
30 MPa	350	650	1150	160	4

Instrumentation and Testing Procedure

All columns were loaded to failure through a vertical hydraulic jack of 600 kN capacity using a steel plate 5 x 5 x 2 cm placed on the top of the column while the base of the column was placed directly on the lower plate (see Figure 2). A computer-controlled data acquisition system was used to record measurements at fixed time intervals. Measurements included load from the load cell and the strains at longitudinal bars from the electrical strain gauges. The test was terminated when the column was fractured.

EXPERIMENTAL RESULTS AND DISCUSSION

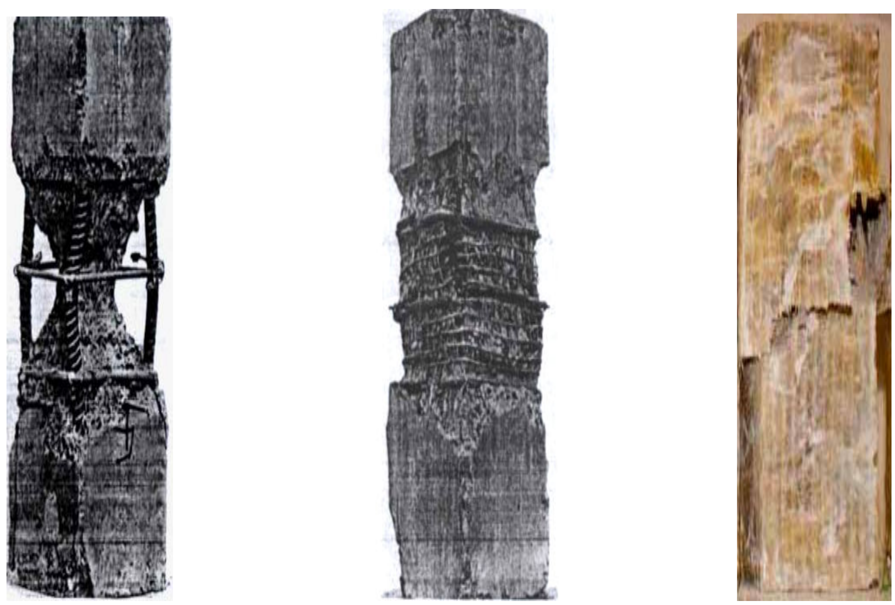
General Behavior of Studied Columns

Typical axial load-axial strain relationships are shown in Figure 3. The ascending branch of the curve was almost linear. Longitudinal cracks occurred at approximately 70% of the ultimate load of the studied column specimens. All the specimens experienced longitudinal cracks and failure load was reached when the extreme compressive fiber crushed. The longitudinal cracks were hidden behind the ferrocement layer and GFRP wraps in column specimens C5 and C6, respectively. The longitudinal cracks eventually led to the spalling of concrete cover and the stiffness decreased gradually and this depended on the confinement of each specimen. For example, the control specimen (C1) lost stiffness quicker than specimens C2, C3 and C4 which were internally confined with additional reinforcement, (i.e. 1% steel fibers, 2% steel fibers and a cage of ESM, respectively). This is in agreement with the findings of Harajli and Rteil [1] and Mau et. al. [6]. The modes of failure of the column specimens, C1, C4 and C6, are shown in Figure 2. It can be seen from the figure that Column, C1, failed in compression by crushing of the concrete core together with buckling of the longitudinal reinforcement at the corner while the confinement using ESM cage for column C4 prevented such buckling of longitudinal reinforcement. Despite that specimen C6 resisted higher loads, the failure occurred without warning as a result of the failure of GFRP composite sheets. The failure was initiated from one corner of the column to midway along the height of the specimen as seen in Figure 2. Despite that the edges of the column specimen C6 were round prior to wrapping with GFRP, it may be argued that the right angles of the corners and the brittleness of the GFRP were the main reason for this type of failure.

Effect of Confinement Type on the Ultimate Capacity and Ductility

Figure 3 shows the load-strain relationships for the studied columns. It can be seen from the figure that generally, the columns confined internally (C2, C3 and C4) and externally (C5 and C6) exhibited higher ultimate loads compared with the control specimen C1. In addition, the ductility of the internally or externally confined specimens, as indicated by the area under the curve was higher than that of the control specimen except for specimen C6 which showed brittle behavior despite the improvement of its ultimate capacity and this was explained earlier. For example, the specimen C2 (containing 1% steel fibers) had an ultimate capacity and maximum strain higher than those of specimen C1 by 9% and 32%, respectively.

Specimen C3 (containing 2% steel fibers) exhibited ultimate capacity and maximum strain higher than those of the specimen C1 by 26% and 52%, respectively. It can be seen from Figure 3 that the behavior of the specimen C4, reinforced by a cage of ESM (vf = 2.2%) is almost similar to that of the specimen C3 (containing 2% steel fibers). In addition, the location of ESM (inside the core, C4, or wrapped around the column as a ferrocement layer, C5) showed a significant difference in the ultimate capacity and ductility of these specimens. For example, C4 had 14% higher ultimate capacity and maximum strain than those of C5. This is in agreement with the findings of Razvi and Saatcioglu [2], Fahmy et al. [3] and Furlong et al. [5]. The specimen C6 showed higher ultimate load compared with all the other studied specimens (37% higher than that of control specimen C1). However, C6 showed brittle behavior compared with the other specimens. This was indicated by the sudden drop in the load at low strain (as a result of the initiation of GFRP sheet failure at the corner of the column). Similar observations were found by Harries et. al. [18].



C1 C4 C6

Figure 2 Failure modes of tested specimens.

APPLICATION OF "ANSYS 5.4" PROGRAM

Research conducted during the past 50 years has resulted in a relatively complete understanding of the variation in the thermal and mechanical properties of both steel and concrete at elevated temperature, and validated mathematical relationships to describe the observed trends [19, 20 and 21]. This is not generally true for FRP materials. In particular, data on the high temperature behavior of FRP is essential for accurate numerical modeling of its fire behavior. Such data is extremely scarce [22]. A pilot study was carried out in this research using ANSYS 5.4 program in order to assess the effect of overheating on the test columns. All of the specimens were simulated with ANSYS (version 5.4) [15], which offers a series of very robust nonlinear capabilities for design and analysis. The coefficient of thermal expansion and the conductivity of glass/epoxy FRP wraps were supplied by the manufacturer. A routine was written in ANSYS to model reinforced concrete columns. Temperature elements were used to study the behavior of the columns prepared in the current investigation in fire conditions. A multi-linear stress strain curves for concrete and steel were considered in the analysis [15]. The full details of the computer program is described elsewhere [15].

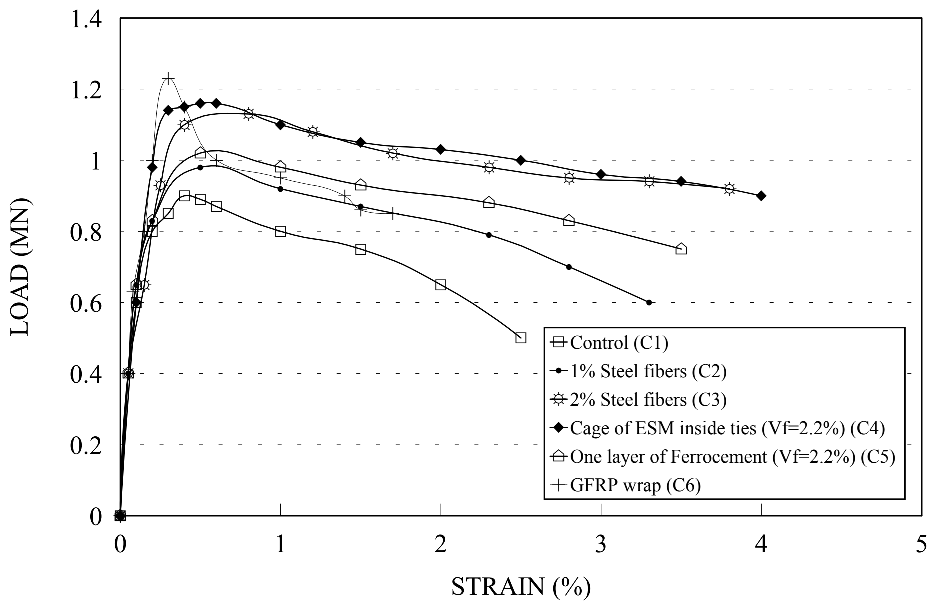


Figure 3 Effect of type of confinement on the load-strain relationships

Concrete and Steel Elements

The concrete were modeled using **SOLID65**, 3-D reinforced concrete solid element (see Figure 4). **SOLID65** was used for the three-dimensional modeling of solids with or without reinforcing bars (rebars). The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x,y, and z directions. This solid element is capable of cracking in tension, crushing in compression, creep, material nonlinearity and large deflection geometrical nonlinearity. The failure criterion of concrete was the William Warnke model with 5 parameters [15]. The peak strength, *f*c, initial young's modulus *E*c, and the other parameters in the model were assigned according to the data in the test. Two shear transfer coefficients, one for open cracks and other for closed ones, were used to consider the retention of shear stiffness in cracked concrete.

The reinforcing bars were adopted using **LINK8** element. **LINK8** is a spar, which may be used in a variety of engineering applications (Figure 5). The three dimensional spar element is a uniaxial tension-compression element with three degrees of freedom at each node. Plasticity, creep, swelling, stress stiffening, and large deflection capabilities are included. The bar was modeled as an elastic perfectly plastic material, and the strength was defined according to the data in the test.

The GFRP sheets were adopted using **SHELL41** element. **SHELL41** is a 3-D element having membrane (in-plane) stiffness but no bending (out-of-plane) stiffness (Figure 6). It is used mainly for shell structures where bending of the elements is of the secondary importance. The GFRP sheets were defined as an anisotropic material. The strength in the perpendicular direction was $1/10^6$ of that in the fiber direction. The ultimate strength and the other properties of the GFRP sheets were supplied by the manufacturer. When the stresses in the GFRP sheet reach its ultimate strength, the calculation stops.

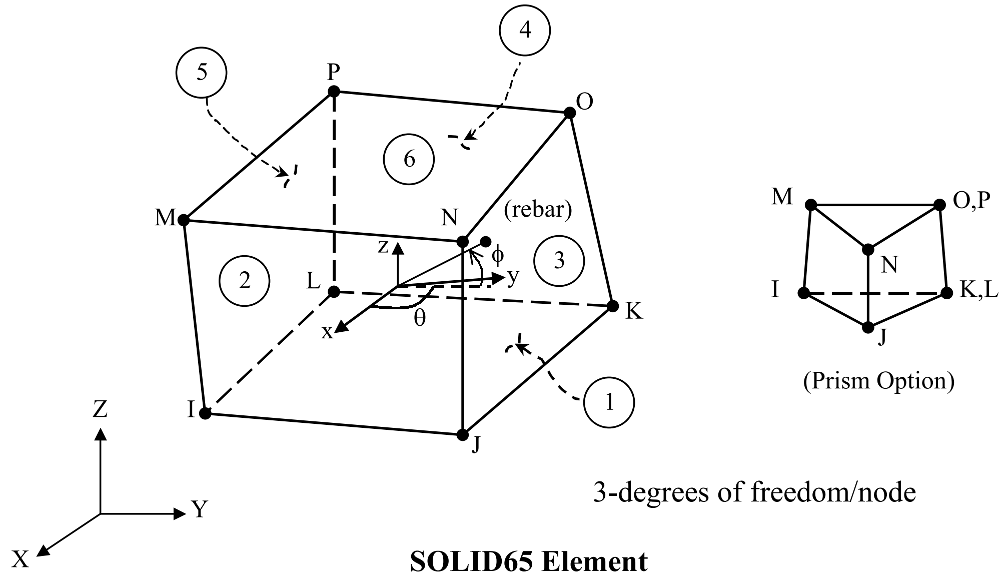


Figure 4 Geometry, nodes and the coordinate system of the 3-D reinforced concrete element

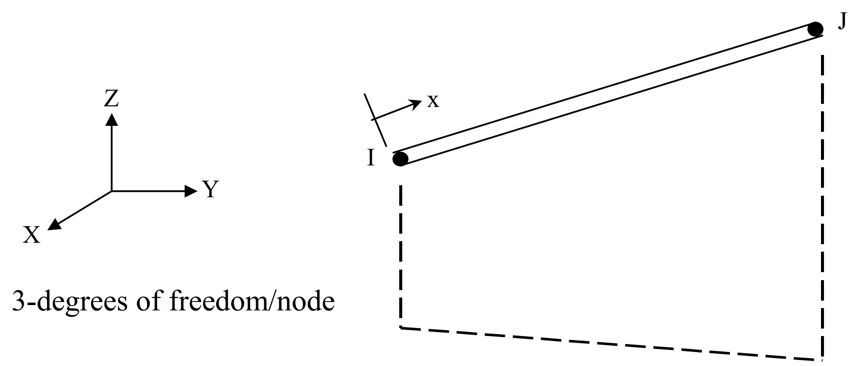


Figure 5 LINK8 3-D spar element.

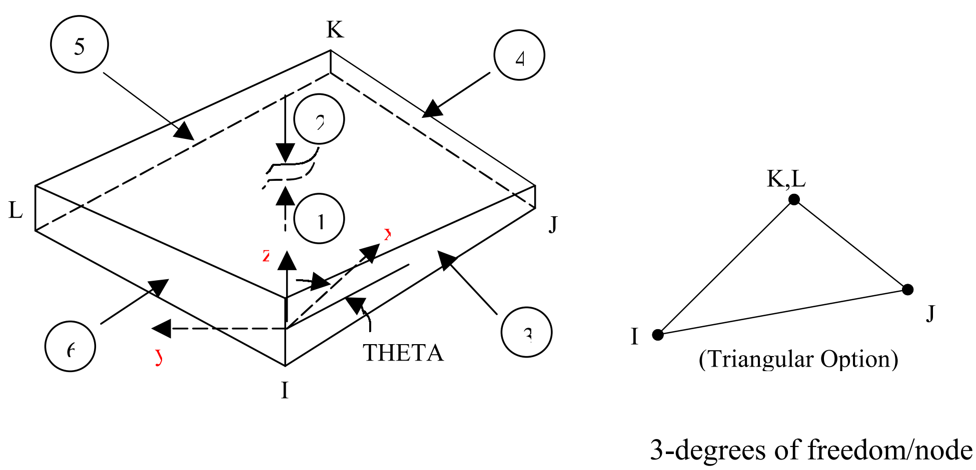


Figure 6 SHELL41 Membrane shell element.

Temperature Elements

SOLID70 has a three-dimensional thermal conduction capability. The element has eight nodes with a single degree of freedom, temperature, at each node (Figure 7). The element is applicable to model a three-dimensional, steady state or transient thermal analysis.

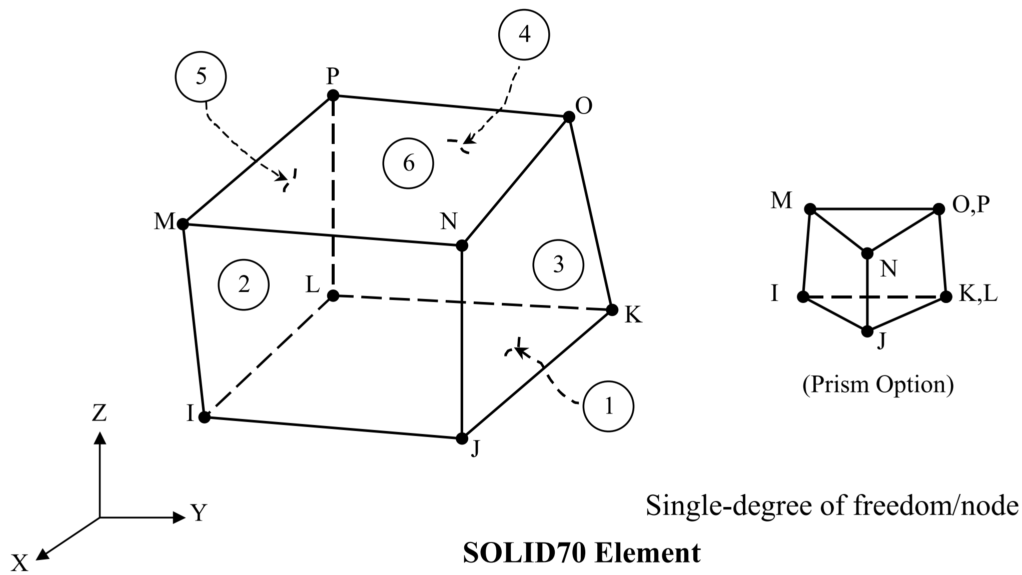


Figure 7 Geometry, node locations and the coordinate system of 3D-thermal element

LINK33 is a uniaxial element with the ability to conduct heat between its nodes. The element has a single degree of freedom, temperature, at each node point (see Figure 8). The conducting bar has the capability for modeling a steady state or transient thermal analysis.

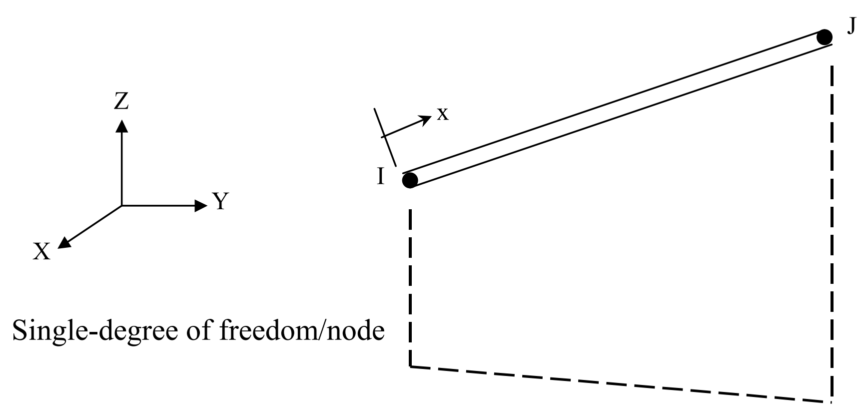


Figure 8 LINK33 3-D conduction bar element.

SHELL57 is a three-dimensional element having in-plane thermal conduction capability. The element has four nodes with a single degree of freedom, temperature, at each node (Figure 9).

Finite Element Modeling of the Studied Columns

Figure (10) shows the finite element mesh of studied columns, automatically generated by the program. It is worth mentioning that all the nodal joints were considered to satisfy displacement compatibilities.

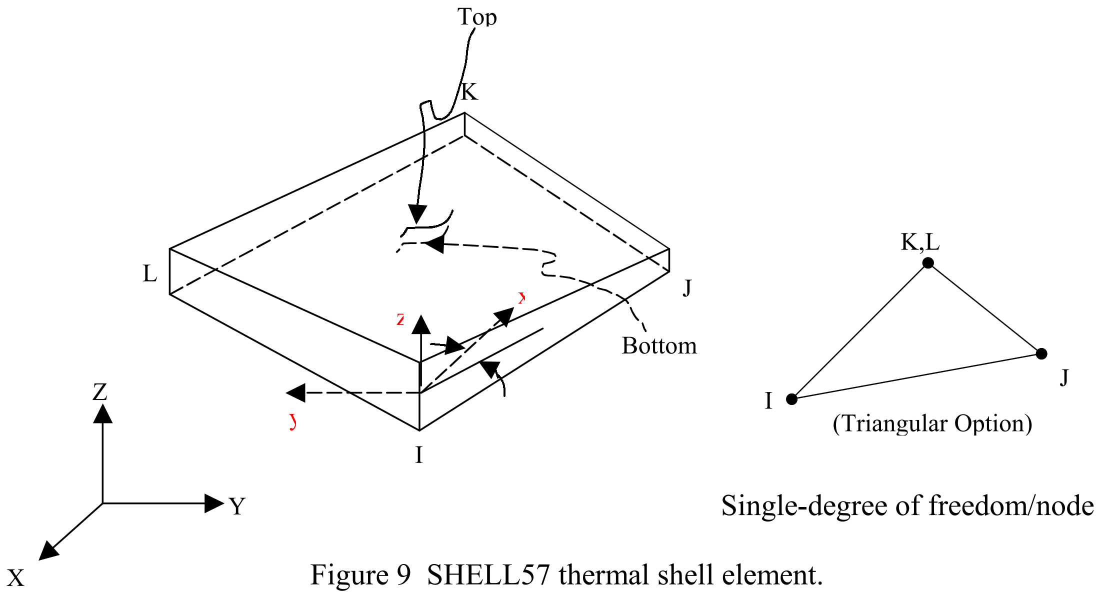


Figure 9 SHELL57 thermal shell element.

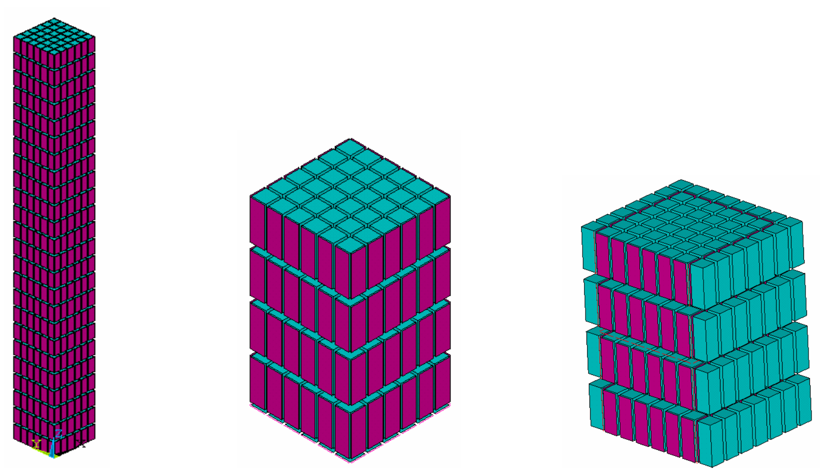


Figure 10 Finite element mesh for column C6

Prediction of the Experimental Results

The columns tested experimentally were modeled using ANSYS 5.4 program under normal temperature conditions. Both of the ultimate load and the axial strain were predicted. The results obtained by the computer program were compared with the experimental results as shown in Table 3. Very good agreement was observed and the maximum difference between predicted and tested ultimate capacity and strains was 5.7% and 12%, respectively.

Effect of Overheating on the Ultimate Capacity of Different Studied Columns

The results obtained from ANSYS for the ultimate capacity of different studied column specimens before and after one hour of fire at 1000 ºC are shown in Figure 11. The strength loss for different studied columns was 46% for C1, 39.2% for C2, 30.5% for C3, 32.6% for C4, 39.1% for C5, and 57.3% for C6. It can be seen that the maximum loss of ultimate capacity was for C6 (GFRP wrapped column) and the minimum loss of ultimate capacity was for C3 (a column containing 2% steel fibers). The results of C6 agree with Bisby's et al. [14] who stated that it is unlikely that the structural effectiveness of FRP materials can be maintained during fire. Chen and Liu [23] reported that FRPs are sensitive to the effects of elevated temperature, with severe degradation of tensile strength and elastic modulus predicted at temperatures below 400° C. In addition, Katz et al. [24] reported that the bond strength between FRP and concrete reduced by 80-90% as the temperature increased from 20-250 ^{o}C. Figure 12 shows the stress distribution in C1 and C6 due to fire. The figure shows that the effect of fire on the specimen wrapped with GFRP, C6 is more aggressive than that for control specimen, C1. This is in agreement with the findings of Mouritz [22], who found that the mechanical properties of the composites are impaired by fire due to thermal degradation and combustion of the polymer matrix.

The minimum loss of strength as a result of fire is shown in Figure 11 for specimen C3. This is in agreement with the results obtained by Poon and Lam [11] who reported that the steel fibers are effective in minimizing the degradation of compressive strength for the concrete after exposure to the elevated temperatures. It can be seen from Figure 11 that the specimen (C4) reinforced with a cage of ESM of reinforcement ratio, vf=2.2% (equivalent to steel fibers ratio, 2%, C3) lost 32.6% of its original ultimate capacity after exposure to fire (almost similar to the behavior of specimen C3). In addition, specimen C5 wrapped with a ferrocement layer showed better behavior compared with control specimen (lost 39.1% of its original ultimate capacity). It can be argued that the ferrocement layer after fire works as a protection layer for the original column before spalling of concrete and melting of the ESM. Bailey [25] reported that the EN version of the Euro-code recommended using a supplementary steel mesh to reduce the risk of spalling. Kalifa et. al. [26], noted that the reinforcement may hold back the concrete scales act as a thermal shield preventing spalling.

Table 3 Prediction of Results Using ANSYS 5.4

Column Specimen Number	Ultimate Load, kN			Strain in Longitudinal Steel, %		
	Experimental	Predicted	Error,%	Experimental	Predicted	Error,%
C1	90	94.8	5.3	0.4	0.36	10
C2	98	92.4	5.7	0.5	0.46	8
C3	113	110.15	2.6	0.8	0.73	8.7
C4	116	120.8	4.1	0.6	0.67	11.6
C5	102	99.2	2.7	0.5	0.56	12
C6	123	129.3	5.1	0.3	0.27	10

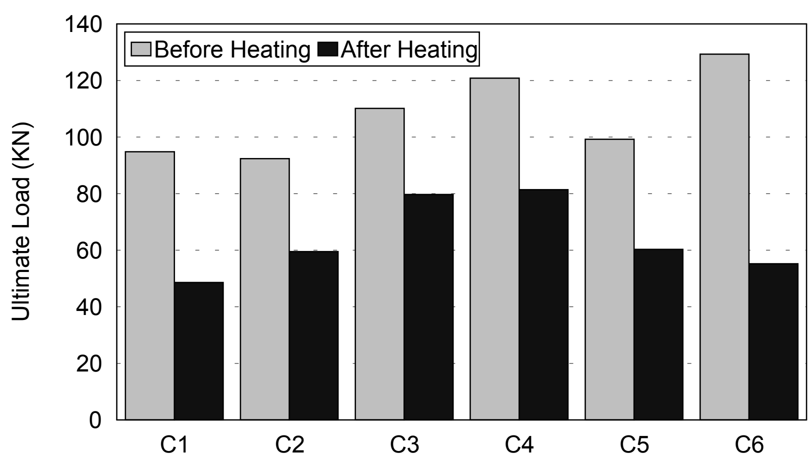
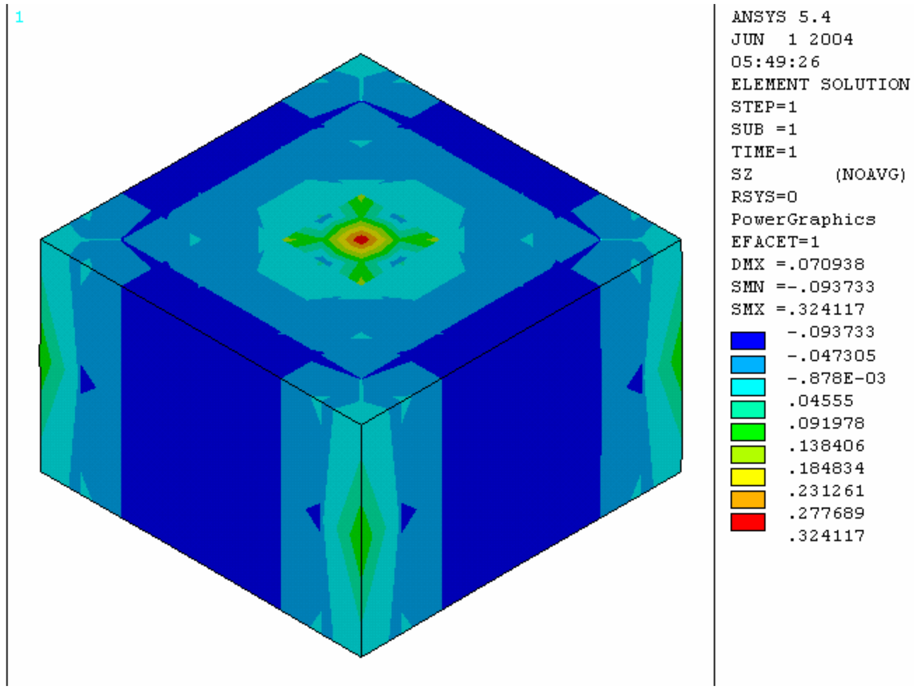
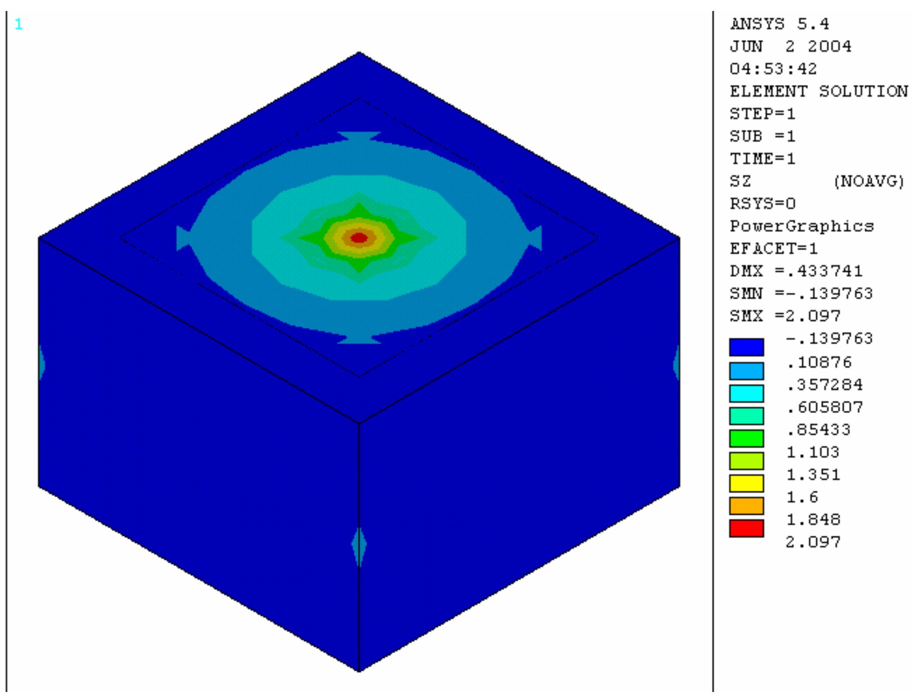


Figure 11 Predicted ultimate capacity of studied columns before and after fire



Stress Distribution for Column C1



Stress Distribution for Column C6

Figure 12 Distribution of stresses due to fire for control specimen and GFRP wrapped one

CONCLUSIONS

In this research the different methods used in confining square R.C columns, internally using steel fibers or expanded metal mesh and externally using ferrocement laminates or GFRP, were evaluated and compared with traditional reinforcement with transverse ties. The effect of fire on the performance of the confining methods was studied using the ready package computer program "ANSYS 5.4" [15]. Based on the work presented above, the following conclusions can be drawn:

[1] The observed modes of failure were similar to those observed by other investigators for the different confining methods.

[2] Ultimate load and ductility of columns tested at room temperatures improved by internal or external confinement except for columns wrapped with GFRP, in which the ductility was not improved in spite of exhibiting the highest ultimate load (37% higher than the control column).

[3] The column with 2% steel fibers and that reinforced internally by a cage of ESM exhibited similar behavior increasing the ultimate capacity and maximum strain by 26 and 52% beyond those of the control column.

[4] Confinement externally by ESM as an external layer of ferrocement gave 14% lower ultimate load and maximum strain compared to the column having identical internal confinement.

[5] To model the thermal behavior of different methods of confinement using the ANSYS 5.4 program, data concerning the material properties was obtained from the manufacturer data sheets or the limited references on the subject. The results of the ANSYS 5.4 reported in this investigation are valid only for the input data used.

[6] The maximum (57.3%) and minimum loss (30.5%) in ultimate capacity was for the columns wrapped with GFRP and containing 2% steel fibers, respectively.

[7] Despite that wrapping with GFRP introduced the maximum ultimate capacity for the studied specimens at room temperatures, but at fire the behavior of FRP wrapped columns deteriorated rapidly.

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