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Quasi-static cyclic tests on super-lightweight EPS concrete shear walls

Seyed Amin Mousavi [a,*], Seyed Mehdi Zahrai [b,c], Asghar Bahrami-Rad [d]

[a] School of Civil Engineering, University of Tehran, Tehran, Iran
[b] Center of Excellence for Engineering and Management of Civil Infrastructures, School of Civil Engineering, Faculty of Engineering, The University of Tehran, Tehran, Iran
[c] University of Ottawa, Ont., Canada
[d] Department of Civil and Environmental Engineering, AmirKabir University of Technology, Tehran, Iran

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ABSTRACT

This study introduces a new emerging structural system, called JK system, which uses JK walls as its main structural elements. JK wall, first proposed by Joseph Kiefer, is a kind of shear wall constructed with low-strength/super-lightweight Expanded Polystyrene (EPS) concrete and reinforced by JK panel, JK stiffener and some additional steel rebars. The study experimentally examines behavior of three JK wall specimens with different reinforcement and level of gravity loads under quasi-static cyclic loading. Obtained results indicate that JK walls can sustain large ductility demands accompanied by stable hysteresis loops. All specimens are also numerically investigated in order to obtain a reliable analytical tool. In this paper, it is shown that a low-strength concrete, currently recognized as a nonstructural material, can be used as a structural concrete having a satisfactory behavior. Finally, a seven story building with JK system is considered to numerically study the above claim. However, more studies are still required to fully capture all short and long term features of structural EPS concrete elements.

1. Introduction

Lightweight materials, especially lightweight concrete, are preferable in terms of both structural features and construction costs. It is basically well understood that as the density of a lightweight concrete decreases, its compressive strength would also decrease. Moreover, virtually all codes, such as ACI-318 [1] and Eurocode-8 [2], have prohibited use of very low strength concrete. While the reason of this restriction has not explicitly mentioned, such limitation is mainly due to durability considerations and lack of studies to some extent. Current codes of practice generally tend to increase durability of concrete only by increasing its compressive strength or by imposing limitations on the value of water–cement ratio. Meanwhile, there are many other techniques to increase durability of concrete without increasing its compressive strength, such as using Expanded Polystyrene (EPS) beads and fly ash [3] or polymer binders [4]. Recently, however, AC 408 [5] recognized this fact and has not imposed any minimum compressive strength for structural concretes with lightweight synthetic aggregates.

In conventional concrete structural systems, such as moment resisting frames and shear walls, there are some limited load paths for transferring gravity and seismic induced loads to the ground. Accordingly, the forces are concentrated in columns, beams, and some limited number of shear walls. In these structures, the level of stress is high and low strength concrete cannot be used. However, in many industrialized modern construction techniques, columns and beams are replaced by bearing walls. In these box-type systems, such as tunnel form [6,7], insolated concrete form, and ICF, all exterior and interior walls are bearing walls which support both gravity and lateral loads. Due to the high redundancy of these box-type systems, level of stress is very low and low strength materials can also be used.

This study focuses on a new emerging bearing wall system, called JK system. The term “JK” stands for Joseph Kiefer who first proposed and constructed JK panels in 1982. The primitive intention of JK panel was on soil stabilization; however its usage in building construction has been recently adopted. JK system is a new type of structural system which uses JK walls to support both gravity and lateral loads. JK walls are concrete walls constructed by low strength/super-lightweight EPS concrete and reinforced by JK panels, JK stiffeners, and some additional rebars. In fact, the used material is EPS mortar as no aggregate was used. However in this study the term EPS concrete is adopted as it shows structural resistance. More details of the JK system would be presented in the subsequent section.

Density of the EPS concrete in JK wall is about 1000 kg/m^3 and its compressive strength is about 5 MPa which cannot be consid-

* Corresponding author. Address: School of Civil Engineering, University of Tehran, 16th Azar St., Enghelab Sq., Tehran, Iran.
E-mail address: s.a.mousavi@ut.ac.ir (S.A. Mousavi).

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ered as structural concrete, according to current codes of practice. The interesting characteristics of JK system are its lightness and its high level of redundancy, such that for a typical 5-story residential building the maximum compressive stress would be less than 0.5 MPa under service loads. Such a low level of stress is also common in conventional concrete box-type systems [8]. Note that for a typical residential building, wall surface (including exterior and interior walls) is about twice the surface of the floors and in box-type structures about 50% of the building dead load comes from the walls. Therefore, reduction in wall weight has a great contribution on reducing the whole dead loads of the building.

One of the main objectives of the current study is to evaluate structural usage of low strength EPS concrete. There is a significant difference between lean concrete (with little cementitious materials) and low strength concrete. A lean concrete is porous and brittle. However, as suggested in earlier studies, EPS concrete is very ductile and can be quite durable using different admixtures such as silica fume or fly ashes. More comprehensive discussion about EPS concrete can be found elsewhere [3,9–12].

There have been many research projects devoted to cyclic behavior of shear walls both analytically and experimentally [13–18], some of them have considered lightweight and others adopted normal weight concrete but in all of them normal/high strength concrete has been used. Summarized results of earlier studies can be found in FEMA306 [19] and its commentary FEMA307 [20].

Structural usage of low strength EPS concrete is not well understood and, to the authors' knowledge, there are very limited published studies about structural usage of very low strength concrete. Hiroaki et al. [21] carried out some experimental studies on coupling beams constructed with low strength concrete and concluded that the behavior of coupling beams with low strength concrete are more ductile compared to that of the same beam constructed with normal strength concrete and with the same reinforcement details. In another study, Mousavi and Bahrami-Rad [22] numerically investigated monotonic behavior of JK wall with low strength EPS concrete. It should be clarified that low strength concrete in this study is referred to a compressive strength lower than 10 MPa.

2. An introduction to JK wall

JK panel is a 3D network of steel strips created by punching and tensioning of a galvanized steel plate with no welding. Currently available dimensions of JK panels are 3 m in height, 1.2 m in width, and 8 cm in thickness. Each strip of the JK panel has a rectangular cross section with thickness of 1.6 mm and width of 5 mm. JK panel provides the main reinforcement steel for the JK wall. JK stiffener is also a truss-like element that its upper and lower chords are fabricated by two galvanized steel rods with diameter of 4.5 mm and its diagonal element is one steel rod with the diameter of 4.5 mm. JK stiffeners pass through JK panels in both vertical and horizontal directions. The main role of JK stiffener is to make the JK panel stiff to facilitate the wall installation. Moreover, they can be considered as additional vertical and horizontal reinforcements.

JK walls are formless due to sticky nature of the used EPS concrete and closely spaced strips of the JK panel. After injection of the EPS concrete into the JK panels, the surface of the wall would be ready to trowel. The above feature of JK wall makes a fast construction procedure especially for mass construction projects. Fig. 1 illustrates different components of JK wall and its concrete injection procedure.

EPS concrete in the JK wall is a mixture of cement, water, EPS beads, sand powder, and glass fiber. However, some additional materials such as silica fume or fly ash and some additional additives like superplasticizer can also be used in the mixture. Besides, glass fiber can be replaced by other appropriate fibers such as Aramid and Polyethylene fibers. More discussions about effect of different fibers on tension softening behavior of concrete are reported by Wang [23] and Wang et al. [24].

EPS concrete should be pumpable without segregation of EPS beads and also it needs to be very sticky. The used EPS concrete (in JK wall) is a dough-like material with virtually zero slump. As a result, the EPS concrete should be injected and it is not suitable for pouring in a formwork. Comprehensive discussion about technology of EPS concrete is out of scope of the current study however roles of each component are presented in Table 1. Used EPS beads have average diameter of 5 mm and density of 12 kg/m^3.

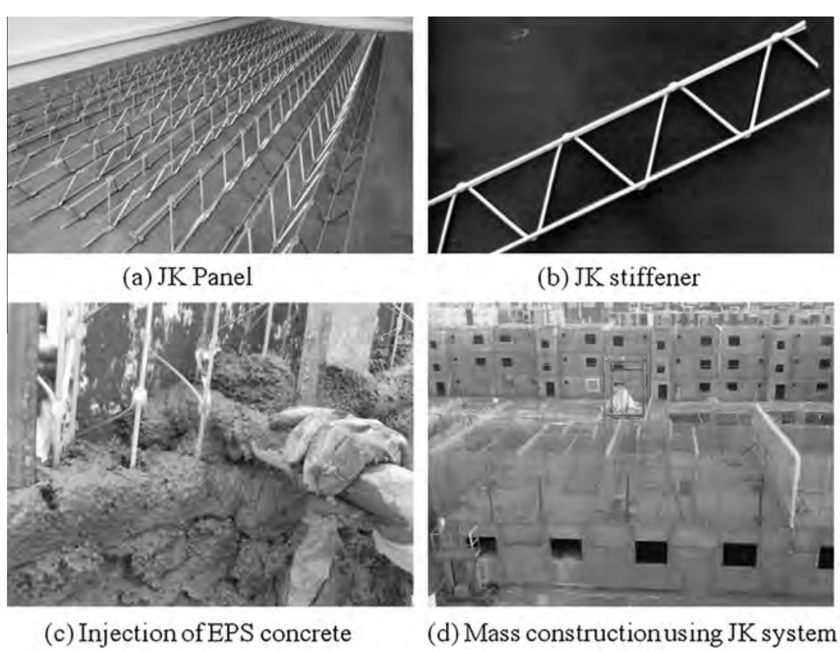


Fig. 1. Components of JK wall and its construction procedure.

Table 1
Role of different materials in the EPS concrete.

Component	Role
Cement and water	Bonding the whole matrix together
EPS beads (average diameter = 5 mm)	Make the matrix lightweight, ductile, and durable
Sand powder (passed sieve #200)	Make the matrix sticky and increase viscosity of the matrix + reduce shrinkage of the matrix + reduce EPS segregation
Glass fibers (average length = 30 mm)	Reduce early shrinkage stains + make the matrix sticky + make a pseudo strain-hardening behavior for the matrix in tension + reduce EPS segregation

Fig. 2 shows surface of the EPS concrete in which EPS beads and glass fibers are quite clear. Generally about 50% of volume of the hardened EPS concrete would be occupied by EPS beads and the rest would be the mortar.

3. Experimental investigation

The main objective of the experimental program is to have a reliable insight of the JK wall performance under cyclic lateral loading. The experimental results are also useful for verification and calibration of numerical models. Moreover, obtained results can be used for structural applications of EPS concrete in other structural systems, such as lightweight floor slab.

3.1. Test units

In order to investigate behavior of JK walls under seismic excitations, three full scale JK walls have been constructed and subjected to quasi-static cyclic lateral loads. Note that all three specimens represent flexural dominated panels in a single story. All specimens have the same dimensions with different horizontal reinforcements and different gravity loads, as presented in Table 2 and illustrated in Fig. 3. The gravity loads is selected according to designed buildings with JK system. For a typical 5-story residential building, developed stresses attributed to gravity loads are below $0.07f_c$, where f_c stands for compressive strength of the EPS concrete. There is no specific design guideline for such low strength concrete in the current codes. Accordingly, reinforcement details of the specimens are selected based upon current practice and some preliminary finite elements analysis.

Preparation of specimens is illustrated in Fig. 4. All specimens were formless and fabricated similar to the current practice. Concrete of the foundation was first poured and the wall concrete has been injected after a 7-day delay.

For each wall, two test specimens have been constructed to decrease damage risks during the transportation of the specimens to the laboratory. Besides, during the construction some steel studs have been used in order to facilitate leveling of the specimens. All studs have been removed after one day.

Table 2
Characteristics of each specimen, A_g refers to the horizontal cross sectional area of the wall.

Wall ID	Vertical reinforcement	Horizontal reinforcement	Gravity load
W1	JK panel + 2 JK stiffeners	3 JK stiffeners + 7Φ8	$0.04f_cA_g$
W2	JK panel + 2 JK stiffeners	3 JK stiffeners + 4Φ8	0
W3	JK panel + 2 JK stiffeners	3 JK stiffeners + 4Φ8	$0.07f_cA_g$

3.2. Material properties

3.2.1. EPS concrete

Mix proportions of foundation and wall concrete are presented in Table 3. Concrete specimens are air-dried and their compressive strength is measured at the age of 33 days. For each mixture, 2 cylindrical samples are constructed and tested.

Concrete samples of the wall are subjected to harmonic displacement-controlled loadings and the foundation samples are tested under monotonic displacement-controlled compression loadings. Stress–strain curves of both samples are shown in Fig. 5. The most interesting aspect of the EPS concrete is its low elastic modulus and its high crushing strain. In other words, EPS concrete can sustain large strains during its elastic range. Elastic modulus of the wall concrete is about 0.55 GPa which is about fifty times lower compared to normal weight concrete. Babu et al. [10] have also reported such small values for the elastic modulus of EPS concrete. According to Fig. 5, the EPS concrete has a great crushing compressive strain and a great ultimate tensile strain which are mainly due to its low elastic modulus. Moreover, in contrast with high strength concretes, the EPS concrete did not experience any sudden explosive failure during the sample level tests.

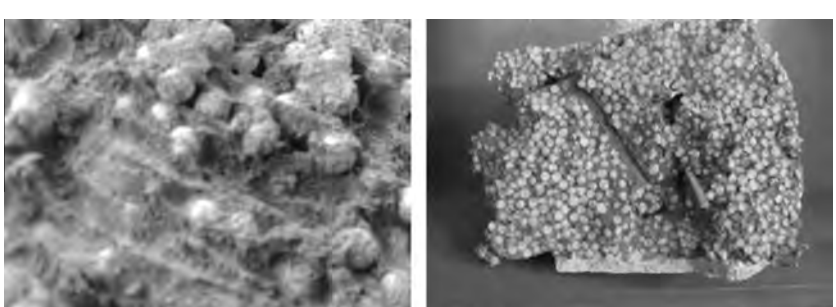
3.2.2. JK panel, JK stiffener and steel rebar

Tensile tests have been carried out for JK panel strips, JK stiffener rods, and the used rebars. Obtained results are all summarized in Fig. 5(c) and Table 4.

The specimen used to measure behavior of the JK panel was cut out from a real JK panel with its inherent out-of-plumbness. As a result, the pre-yield portion of its behavior has some minor irregularity. Such imperfection in JK strips would definitely exist in a real JK wall which according to Fig. 5(c) can be neglected.

3.3. Test setup

Figs. 6 and 7 illustrate the setup used in the experimental program. Eight LVDTs were used to capture displacements of the specimens at different locations. Two LVDTs were used for slip



(a) Glass fibers in EPS concrete (b) EPS concrete with no segregation

Fig. 2. EPS concrete used in JK wal.

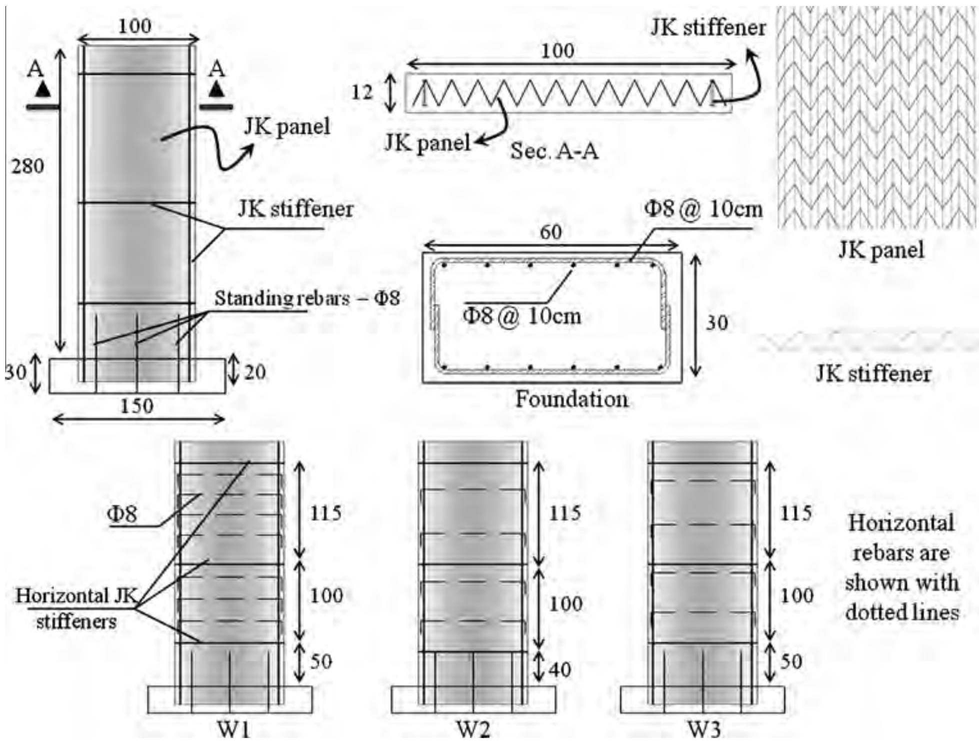


Fig. 3. Details of the test specimens (all dimensions are in centimeters).

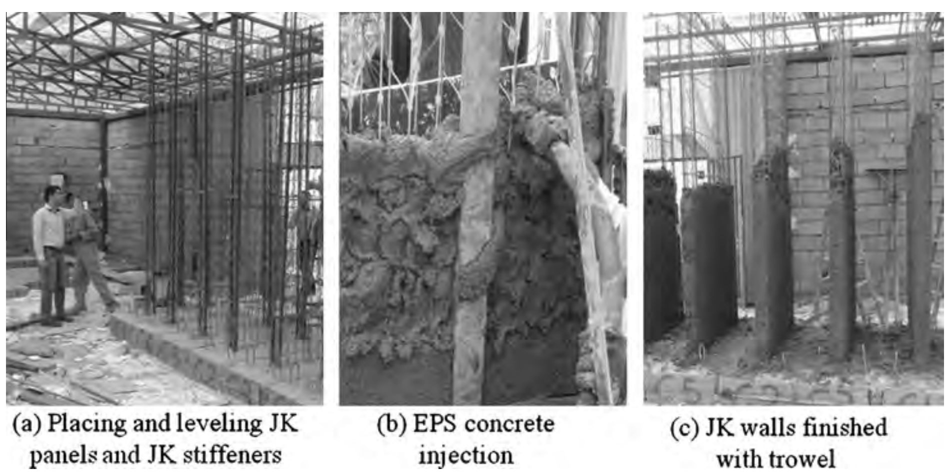


Fig. 4. Preparation of test specimens.

Table 3
Adopted mix proportion for the EPS concrete.

	Cement (kg)	Water (kg)	Sand powder (kg)	EPS bead (kg)	Glass fiber (kg)	Wet density (kg/m^3)	Dry density (kg/m^3)	Average compressive strength (MPa)-33 days
Wall	515	240	380	13.2	5.6	1155	1043	5.5
Foundation	685	350	490	7	2.9	1534	1353	6.30

displacement of the foundation, two others were devoted to slip shear of the wall at wall/foundation connection, and two LVDTs were responsible for measuring displacement of the wall at one meter elevation from top of the foundation. In order to measure out-of-plane displacement of the wall, two other LVDTs were also used at the middle of the walls in the out-of-plane direction. No LVDT was used at the top of the wall due to the capability of the actuator which had an advanced built-in LVDT to capture the displacement at its own level.

Loading history of the specimens has been selected according to FEMA 461 [25] protocol. The protocol is quite straightforward and there is no need to estimate yielding force of the wall. First of all, targeted smallest deformation amplitude should be selected. Note that this parameter represents any small deformation amplitude

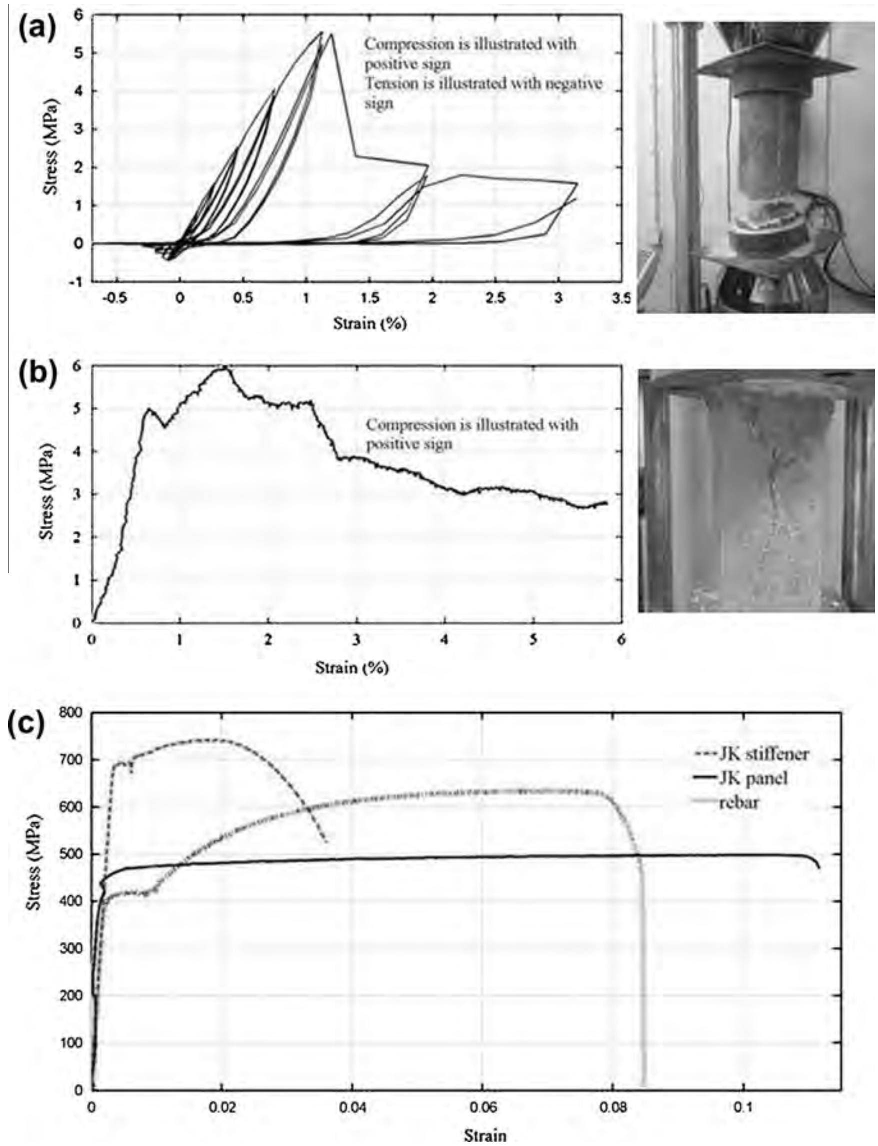


Fig. 5. Stress–strain curves for the used materials; (a) concrete of the JK wall, (b) concrete of the foundation, and (c) different reinforcements used in the JK wall.

Table 4
Mechanical properties of different used steel.

	Yield stress (MPa)	Elastic modulus (GPa)	Ultimate stress (MPa)	Ultimate strain
Rebar-steel	420	190	630	0.077
JK panel-galvanized steel	470	210	500	0.11
JK stiffener-galvanized steel	690	205	740	0.02

such that the wall requires at least six subsequent cycles to the beginning of the lowest damage state. As shown in Fig. 7(d), the loading history includes series of double cycles such that the amplitude of each double cycle group is greater than its previous double cycle by 40%. The cyclic loading is continued until occurrence of significant strength degradation. The targeted smallest deformation amplitude in this study is considered to be 2.6 mm and the loading is imposed with the frequency of 0.02 Hz.

4. Experimental results

4.1. General observations

As shown in Fig. 8, all three JK walls suffered localized damage during the cyclic tests such that virtually all damages occurred at the lower 50 cm of the specimen. This is mainly due to the flexural behavior of the specimens and nature of the EPS concrete which tends to localize damage. This tendency of EPS concrete was also seen during compression tests on cylindrical samples and has been observed in earlier studies as well [10]. During the tests, some strips of the JK panel buckled under compression, mainly at boundaries, while no buckling was observed on JK stiffeners. No out-of-plane buckling occurred and all three specimens failed under flexure/boundary-zone compression. According to FEMA 307 [20], ductility ratio for such failure mechanism would range from 4 to 8, consistent with the obtained results of this study. It is worth noting that definition of a high ductile element slightly varies in different codes of practice. For example, according to FEMA 307 [20], ductile elements should have ductility ratio greater than 5, however according to FEMA 356 [26] and ASCE 41 [27] this threshold

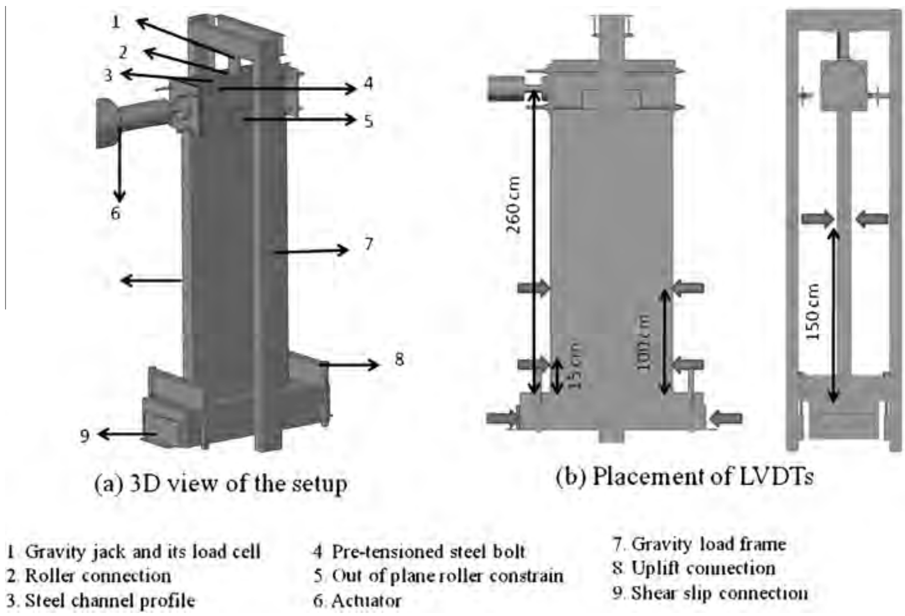


Fig. 6. Schematic setup for the tests.

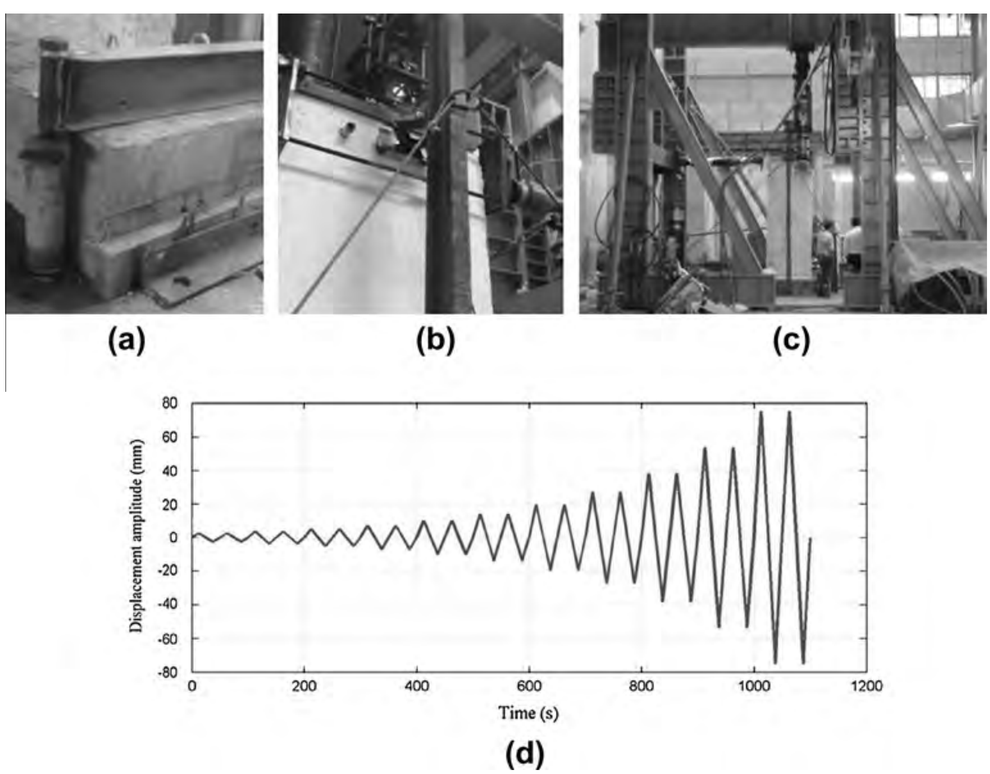


Fig. 7. Test setup, (a) strong floor-foundation connection, (b) details of imposing vertical and lateral loads, (c) supporting frame of the actuator, and (d) loading history.

is 4. Moreover, according to Eurocode 8 [2] an uncoupled wall with a high level of ductility should have ductility ratio greater than 4. The value of 4, therefore, is adopted in the current study as the high ductility threshold. Note that the tested specimens are full scale so obtained ductility capacities can be directly compared with those of codes of practice.

Cyclic behavior of the specimens and its corresponding envelope idealized bilinear curves are shown in Fig. 9. Envelope curves are idealized with bilinear technique per FEMA 356 [26]. It is assumed that the displacement, at the post peak region, with corresponding capacity less than 85% of the maximum capacity is not reliable and represents the collapse point of the bilinear curve. In drawing all bilinear curves, the aforementioned failure point is assumed to be the target displacement per FEMA 356 [26]. Table 5 presents the main parameters of the obtained cyclic loops. Maximum capacity of each specimen is estimated using the well-known equivalent rectangular stress block. As given in Table 5, the equivalent rectangular stress block can be effectively used in the case of low strength/super-lightweight EPS concrete. However, compressive strain limit of 0.003 should be increased to 0.01 as EPS con-

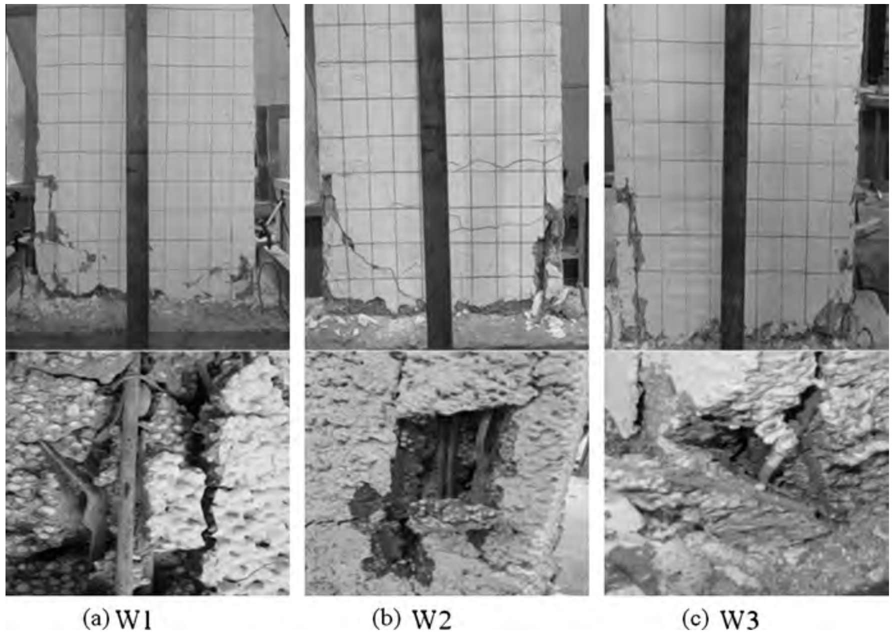


Fig. 8. Damaged JK walls after the cyclic tests.

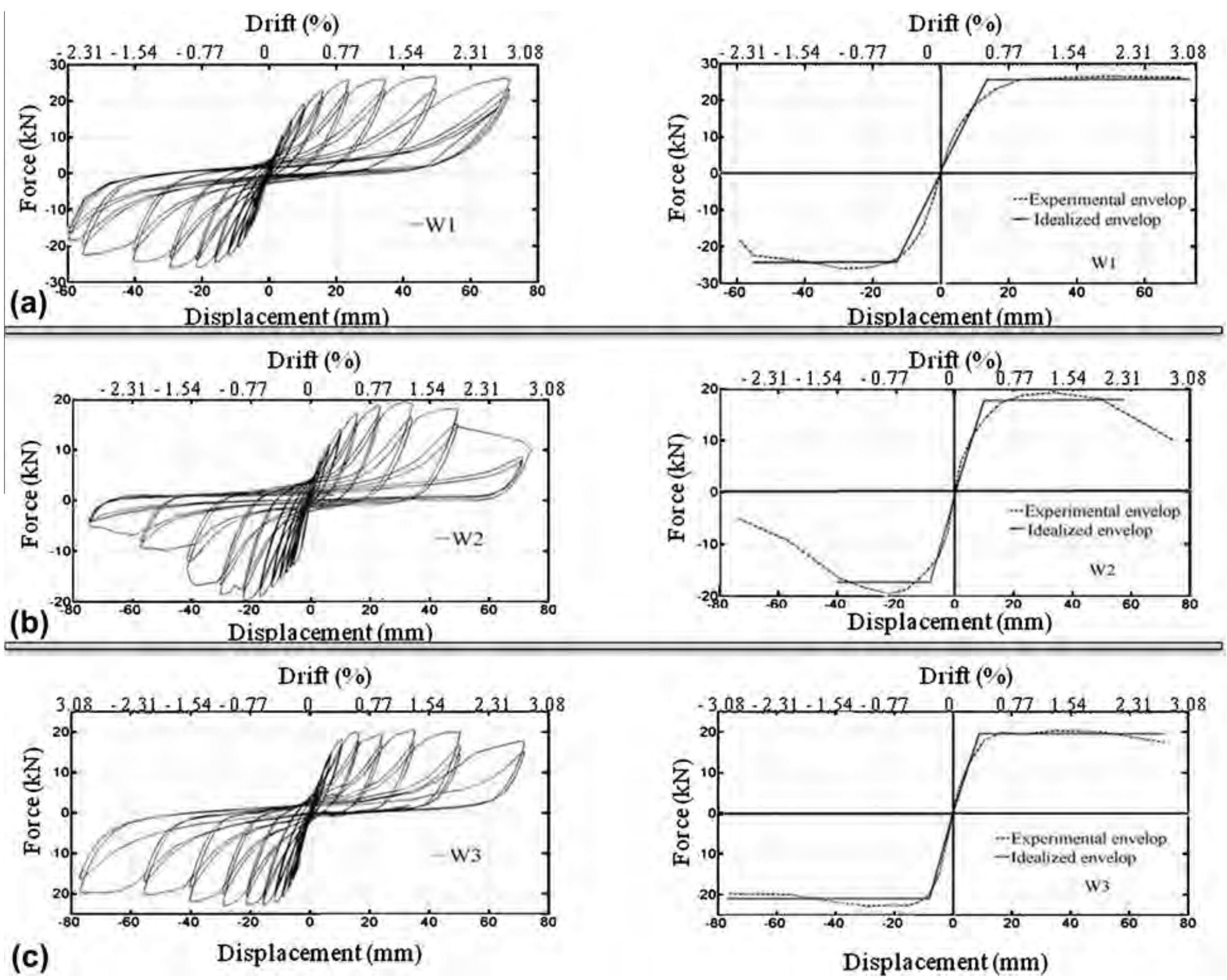


Fig. 9. Hysteresis loops, envelope curves, and corresponding idealized bi-linear curves; (a) W1, (b) W2, and (c) W3.

Table 5
Important parameters from the observed cyclic loops.

ID	Estimated maximum capacity (kN)	Measured maximum capacity (kN)	Effective yield capacity (kN)	Yield displacement (mm)	Maximum reliable displacement (mm)	Ductility ratio	Level of ductility
W1	21.6	26.2	25	12	63	5.2	High
W2	18.8	19.4	17.5	10	48	4.8	High
W3	24.1	21.5	20.3	8.5	74	8.7	High

crete can sustain more strains in its pre-peak behavior. Such a large strain capacity is not a general characteristic of all EPS concretes. Depending on aggregate amount in the mixture, its crushing strain can vary from 0.003 to 0.01. Babu et al. [10] suggested that EPS concretes can have crushing strains as small as normal weight concretes, i.e. about 0.003. Comparison of the obtained results in this study with results of earlier studies reveals the fact that only a small amount of aggregate can rapidly decrease crushing strain of the EPS concrete.

All three specimens have shown some minor difference on their behavior in positive and negative directions and Table 5 presents the average values in positive and negative directions.

According to Fig. 9, all specimens experienced high level of pinching on their cyclic behavior. This is not a surprise as pinching is common among concrete shear walls [20] and also in reinforced masonry walls [28,29]. Among different reasons of pinching, sliding of vertical JK stiffeners and opening/closing of cracks are more pronounced in the current study.

Table 6
Comparison of ductility ratio for different shear walls.

Reference	Wall	Aspect ratio	Gravity load	Ductility ratio
Current study	JK wall-W3	2.6	$0.07f_cA_g$	8.7
Dan et al. [30]	High strength concrete shear wall	2.6	$0.016f_cA_g$	4.8
Dazio et al. [14]	High strength concrete shear wall	2.3	$0.1f_cA_g$	7.4
Dazio et al. [31]	Hybrid fiber concrete shear wall	2.8	$0.015f_cA_g$	7

4.2. Ductility

As stated earlier, JK wall can sustain large ductility demands due to the specific features of its EPS concrete. The used EPS concrete has a quasi-strain hardening behavior in tension and can sustain large strains in compression. These two features of the EPS concrete make the JK wall quite reliable in terms of ductility requirements. To compare JK wall with normal weight/high strength concrete shear walls, obtained results of this study are compared with earlier studies in Table 6.

4.3. Energy dissipation

Total dissipated energies of W1, W2, and W3 are 7.2 kN m, 5.2 kN m, and 5.9 kN m, respectively. Cumulative dissipated energies according to different displacements are depicted in Fig. 10. Again a stable behavior is observed in dissipated energy as displacement increases. Envelopes of these curves indicate that cumulative dissipated energy has a linear relation with displacement. The authors would like to clarify that dissipated energies are calculated based on the measured cyclic loops of Fig. 9. A simple algorithm is written to obtain cumulative dissipated energy corresponding to each increment of the imposed displacement.

4.4. Effect of gravity load

Due to the fact that most of the nonlinearities occurred in the lower 50 cm of the specimens where reinforcement details of all specimens are the same, observed difference on cyclic behavior can be mainly attributed to the imposed gravity load. Results indicate that the best level of normalized gravity load is 4% in which

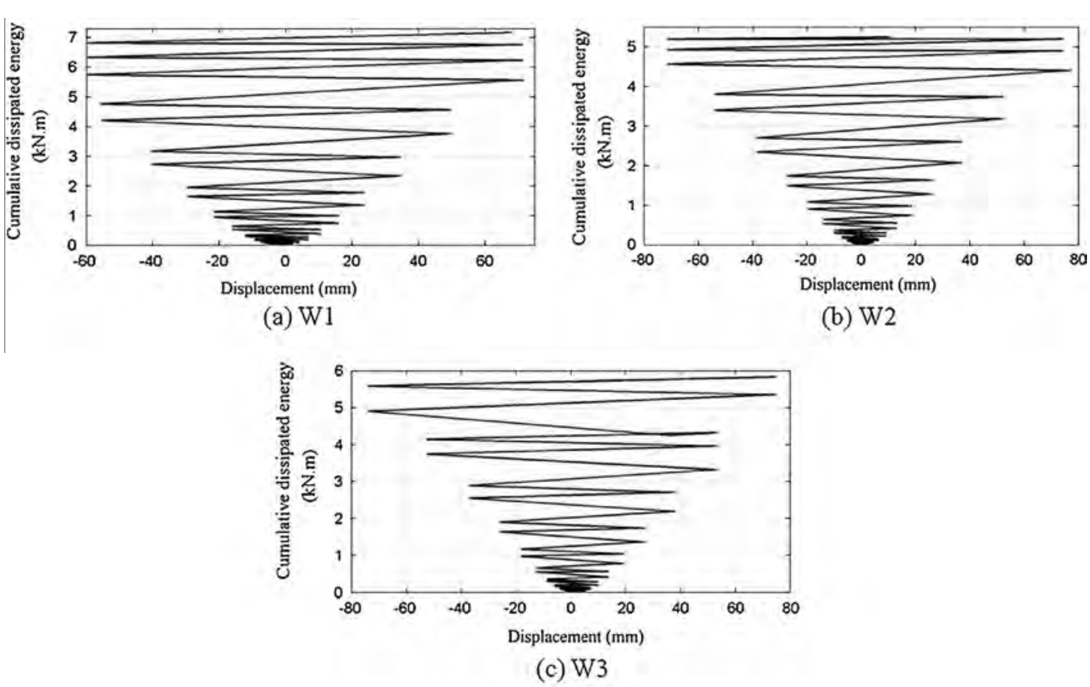


Fig. 10. Cumulative energy dissipation in different displacements.

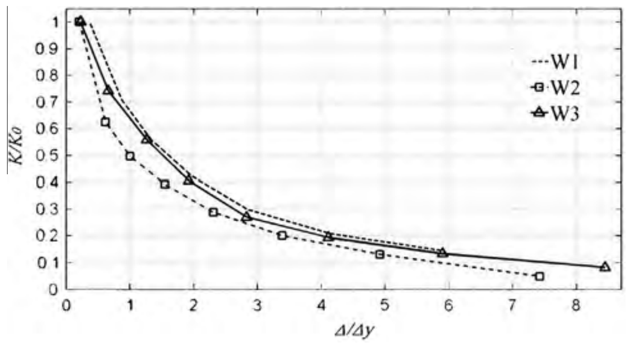


Fig. 11. Stiffness degradation of specimens; K_0 and Δ_y stand for initial stiffness and yield displacement, respectively.

energy dissipation has its maximum value. In the case of JK wall, axial load increases ductility ratio of the wall as it delays flexural tensile cracking at the wall edges. However, normalized axial loads more than 4% reduce energy dissipation capability of the JK wall as crushing and spalling of EPS concrete would occur sooner. Generally speaking, it is believed that axial load has an inverse relationship with ductility of concrete shear walls. As a result, and due to the limited number of tested specimens, no general conclusion can be made in terms of axial load-ductility interaction of JK walls.

4.5. Stiffness and strength degradation

According to Fig. 9, JK walls did not experience any significant strength degradation except W2 where suffered major horizontal cracks on its base during the test. This is mainly due to absence of gravity load in this specific specimen. Stiffness degradations of specimens are presented in Fig. 11. Specimen W2 which has no gravity load experienced the most severe stiffness degradation. The illustrated patterns for the stiffness degradation are very similar to those reported by Dan et al. [30] for high strength concrete shear walls. Aspect ratio of the specimens in this study is the same as those in [30]. It is interesting to note that, according to ACI 318 [1] stiffness factor of an uncracked wall ($\Delta/\Delta_y = 1$) is 0.7 which is in agreement with Fig. 11. Again per ACI 318 [1], stiffness factor of a cracked wall is 0.35. Note that according to definition of ACI 318 [1], cracking point of a wall corresponds to its maximum capacity. According to Fig. 9, this point approximately corresponds to $\Delta/\Delta_y = 2$ and from Fig. 11 at this point, stiffness ratios of all specimens are close to 0.35.

5. Modeling

Before beginning the section, the authors would like to elaborate that experimental results can be used whether as verification or calibration tools. During the verification process, numerical model is constructed according to physical and mechanical properties of the tested specimens and the results would be compared with experimental results. However, during the calibration process parameters of the constructed model would be adjusted according to experimental results. Accordingly, a verified numerical model can be extended in other cases, while a calibrated model cannot be used in other cases.

In this study, both verification and calibration models are constructed using the general purpose finite element package, Abaqus V 9.11 [32] and the nonlinear analysis program IDARC 2D [33], respectively. Different characteristics of the used EPS concrete and steel reinforcements are selected according to obtained experimental results which are presented in Fig. 5. However, at the experimental program, according to the provided embedment length for the vertical JK stiffeners, only 100 MPa can be developed in these elements while their ultimate capacity is about 740 MPa.

5.1. Simulation using Abaqus – a verified model

A damaged plasticity model is adopted for the EPS concrete and all concrete components are modeled with 8-node solid elements. JK panel, JK stiffener, and rebars are modeled with beam elements and they are embedded into the so called 8-node solid concrete elements, as shown in Fig. 12.

All three specimens are constructed and analyzed under monotonic loading. As shown in Fig. 13, Abaqus can estimate capacity of JK wall quite well. However, it cannot accurately account for pinching effect on cyclic behavior of reinforced concrete elements. This feature was also suggested earlier by Wan et al. [34]. Cyclic behavior of JK walls can be simulated by IDARC. However, IDARC needs experimental results to calibrate its pinching parameters. It should be pointed out that results of the monotonic loading are valuable as JK walls would be designed per performance based philosophy.

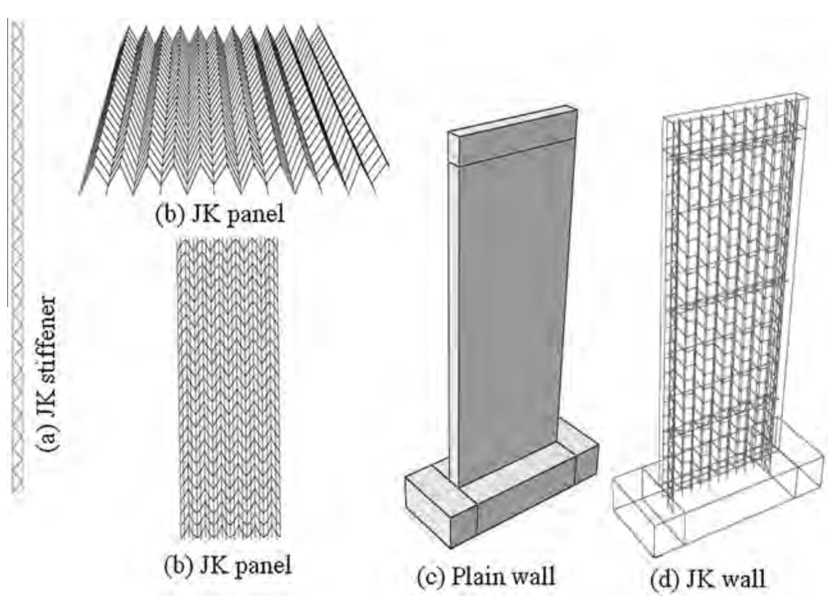


Fig. 12. Different modeled components of JK wall in Abaqus.

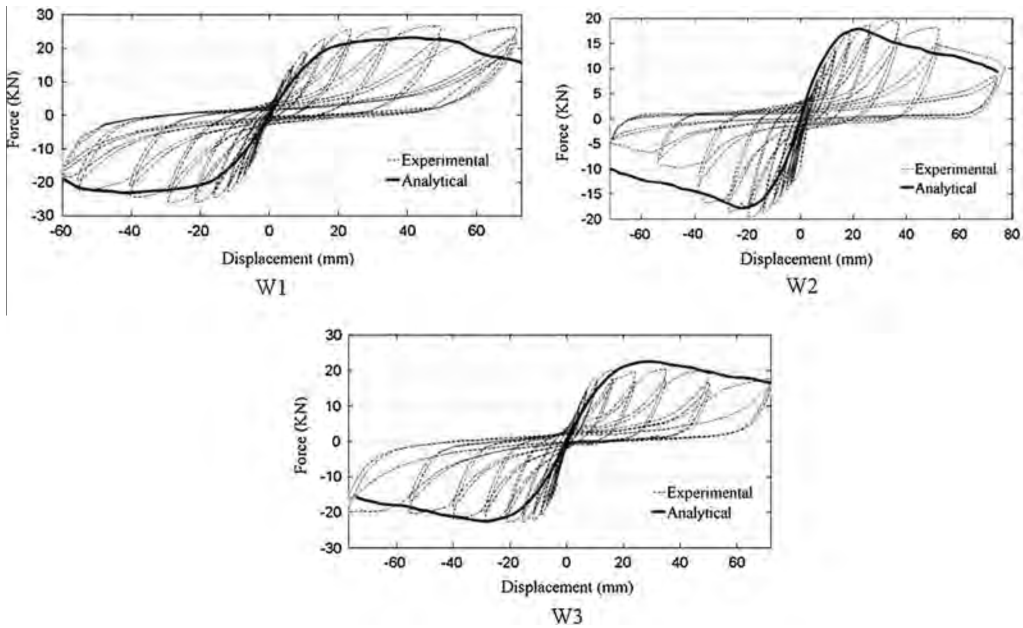


Fig. 13. Validity of the verified numerical models in Abaqus.

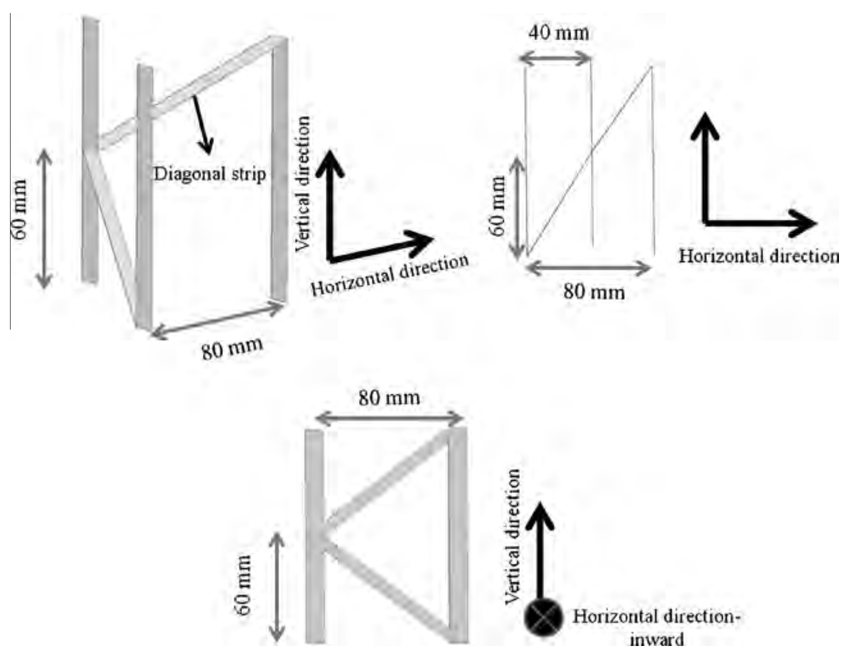


Fig. 14. Detailed dimensions of JK panel strips.

5.2. Equivalent reinforcement for JK panel

JK panel is geometrically complicated and cannot be directly modeled in conventional numerical software. Therefore, defining an equivalent reinforcement, rather than a direct modeling approach, is preferred. According to geometrical features of the JK panel, as shown in Fig. 14, its equivalent reinforcement can be obtained by projecting their 3D strips in two vertical and horizontal axes. Obtained results are summarized in Table 7. Note that diagonal strips have no contribution on vertical equivalent reinforcement as they are not continuous in that direction.

Equivalent horizontal reinforcement can be obtained using Eqs. (1) and (2). In these equations, A and E denote cross sectional area and elastic modulus of the diagonal strip in its axial direction, respectively, and A_{eq} and E_{eq}, respectively, represent cross sectional area and elastic modulus of the equivalent horizontal reinforcement. Moreover, f_y is yielding stress of the used steel.

$$A_{eq}f_y = Af_y \cos 34^\circ \cos 63^\circ \rightarrow A_{eq} = 0.37A = 3\ \mathrm{mm}^2 \quad (1)$$

$$(E_{eq}A_{eq}/40) = (EA/10.7)\cos^2 34^\circ \cos^2 63^\circ \rightarrow E_{eq} = 0.14E = 29\,\mathrm{GPa} \quad (2)$$

To validate the obtained results, a unit wall with length and height of 1 m and thickness of 120 mm constructed with EPS concrete and reinforced by JK panel, with no JK stiffener, is modeled and subjected to six monotonic loading states, as depicted in Fig. 15. Two modeling techniques are examined for the equivalent reinforcement technique as follows,

– Unit equivalent wall with 8-node solid elements in which the equivalent reinforcements are embedded into the wall.

Table 7
Characteristics of the equivalent reinforcement.

	Equivalent reinforcement	Elastic modulus of the equivalent reinforcement (GPa)
In vertical direction	8 mm^2 @ 40 mm	205
In horizontal direction	3 mm^2 @ 120 mm	29

– Unit equivalent wall with shell elements in which a multilayered shell is defined and the equivalent reinforcements are modeled as reinforcement layers.

From Fig. 15, it is clear that the equivalent reinforcement technique can simulate real behavior of the JK panel with good accuracy. JK panel provides good confinement for the EPS concrete due to its 3D geometric nature. This feature cannot be simulated by the equivalent reinforcement technique. That is why in Fig. 15, the equivalent reinforcement technique underestimated post peak compressive behavior of the unit wall. However, the technique is still valuable as in practical designs, compressive strain of the EPS concrete would be limited to its crushing strain which is about 1% and up to this strain, accuracy of the equivalent reinforcement technique is quite good.

5.3. Simulation using IDARC – a calibrated model

IDARC 2D is a nonlinear program mainly developed for estimating hysteresis behavior of reinforced concrete elements. All specimens are modeled with smooth hysteresis model and its parameters are calibrated according to the obtained experimental results, as presented in Table 8. Detailed discussions about such parameters are explained by Sivaselvan and Reinhorn [35]. In Table 8, α is the parameter responsible for the stiffness degradation, β_1 and β_2 represents strength degradation due to ductility and energy dissipation, respectively. N is the parameter for the transition smoothness of the curve from linear to nonlinear zone; η governs the shape of unloading path and finally, R_s, σ, and λ define the shape and severity of the pinching. Equivalent reinforcement technique developed in the previous section is also used in this section. Fig. 16 shows obtained analytical results using IDARC and compares them with the experimental ones. Again, note that the obtained parameters in Table 8 are exclusive to adopted specimens and cannot be generalized for other JK walls with other reinforcement details or aspect ratios. More experimental works are needed for such generalization.

5.4. System level simulation

In order to have a thorough insight of the JK system, behavior of different JK walls with different configurations should be investigated. Therefore, using the previously verified model (not cali-

Table 8
Calibrated smooth hysteresis parameters used in IDARC.

Specimen	α	β_1	β_2	N	η	R_s	σ	λ
W1	50	0.95	0.85	1	10	0.37	0.2	0.05
W2	50	0.99	0.93	1	6	0.4	0.1	0.05
W3	50	0.99	0.9	1	10	0.4	0.2	0.05

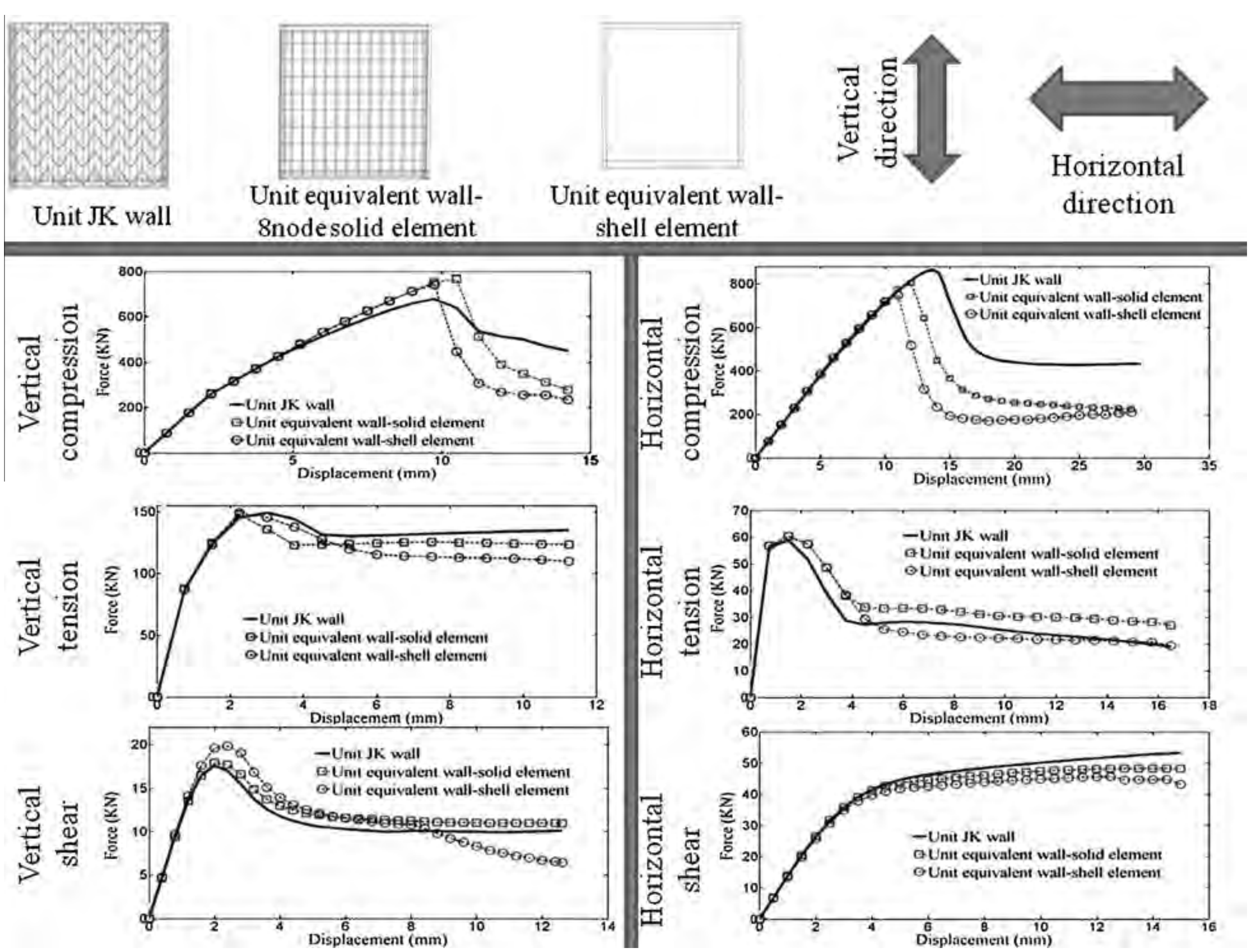


Fig. 15. Validity of the equivalent reinforcement in different loading states.

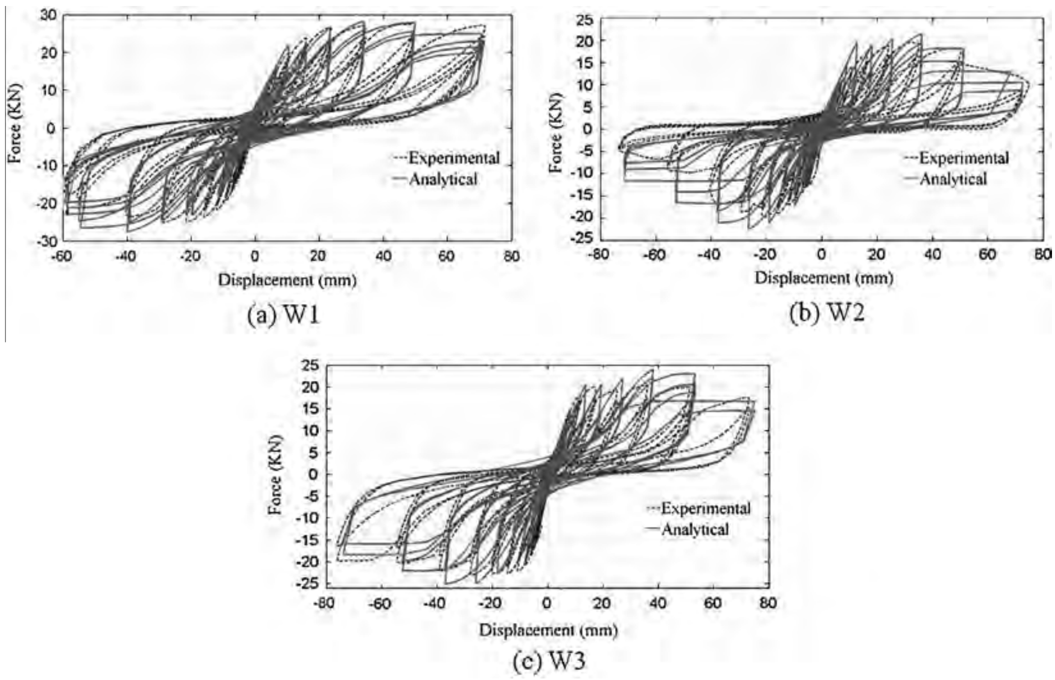


Fig. 16. Validity of the calibrated analytical models in IDARC.

brated model), a seven-story building with JK system is considered to evaluate its performance under seismic excitation. Tributary slab widths for all walls are considered to be 2.5 m in all stories. Dead and live loads of the building are assumed to be 3 kN/m^2 and 2 kN/m^2, respectively. Floor slabs of all stories are constructed with lightweight EPS concrete, that is why the dead load of the floor is lower than conventional floor slabs. The building is subjected to monotonic lateral loading and its pushover curve is obtained per FEMA 356 [26]. Fundamental period of the building is 0.81 s and its first modal mass participation is 75%. It is obvious that JK system is not as stiff as conventional bearing wall systems due to the used EPS concrete which has a low elastic modulus. Lateral loads are distributed according to the first mode shape of the building. All JK walls have 12 cm thickness and reinforced with JK panels, JK stiffeners, and rebars with diameter of 10 mm. It should be noted that vertical and horizontal JK stiffeners are spaced per 50 cm and 100 cm, respectively; and horizontal rebars are spaced by 30 cm. Such reinforcement gives a reinforcement percentage of about 0.25% which is the minimum reinforcement for special shear walls per ACI-318 [1]. Different dimensions of the building, its pushover curve, and damage states of the building are all summarized in Fig. 17. Note that in Fig. 17(c), white highlights represent regions that failed to satisfy LS acceptance criteria. This is just an illustrative example, so only one lateral load distribution and only one direction is considered. Out-of-plumbness and other imperfections are considered in the model using the applied out of plane pressure on some walls at different stories and non-symmetric boundary conditions. The building is modeled with multi-layer shell elements in Abaqus according to the previously defined equivalent reinforcement technique.

The building is located in Tehran which has a level of seismicity equivalent with seismic design category D per ASCE 7 [36]. Iranian Seismic provision, Standard No. 2800 [37], suggests that response spectrum acceleration on stiff soil (with shear wave velocity of about 250 m/s, soil type III per Standard No. 2800 [37] and soil type D per ASCE 7 [36]) and in Tehran is 0.87 (corresponding to period of 0.81 s). Therefore, the target displacement of the building, according to FEMA 356 [26], would be,

$$\delta_t = C_0C_1C_2C_3S_agT_e^2/(4\pi^2) = 1.5\times1\times1\times1\times0.87\times9.81\times T_e^2/(4\pi^2)$$
$$= 0.325T_e^2 = 0.325\times0.81^2 = 0.213\,\text{m} \quad (3)$$

Note that, according to Fig. 17, effective period of the building (T_e) is very close to its initial elastic period. All of the presented parameters in Eq. (3) are defined in FEMA 356 [26] and their definitions are not repeated here due to space limitation. Moreover, different limit states (acceptance criteria) of the JK system are proposed in the subsequent section. From Fig. 17(c), it is obvious that some limited regions in the lower three stories failed to satisfy LS criteria and they need to be strengthened. This can be done either by imposing more reinforcement or by increasing thickness of the wall. That is to use double JK wall in the lower three stories.

6. Design considerations

The following considerations are proposed based upon obtained experimental and numerical results in this study as well as earlier practical experiences obtained from construction with JK system.

6.1. Performance-based design

Due to the current developments on nonlinear finite element software, a nonlinear static, or quasi-static, analysis can be simply used in order to estimate behavior of the JK system under a predetermined level of seismic hazard. In order to design the building according to performance-based philosophy, some acceptance criteria should be defined first. Per ATC-40 [38], deformation capacity at the collapse prevention (CP) level is the deformation at which capacity of the component significantly falls down and the life safety (LS) level is defined to be 25% lower than CP level. However, using more conservative percentage, i.e. 30% rather than 25%, is more reasonable due to the fact that JK system is an ongoing technology and all detailed behaviors of this system are not still well-understood. As presented in Table 9, some simple yet efficient strain-based acceptance criteria are introduced for JK system such that concrete crushing and reinforcement rupture in any direction would be prohibited. These criteria are adopted due to the fact that

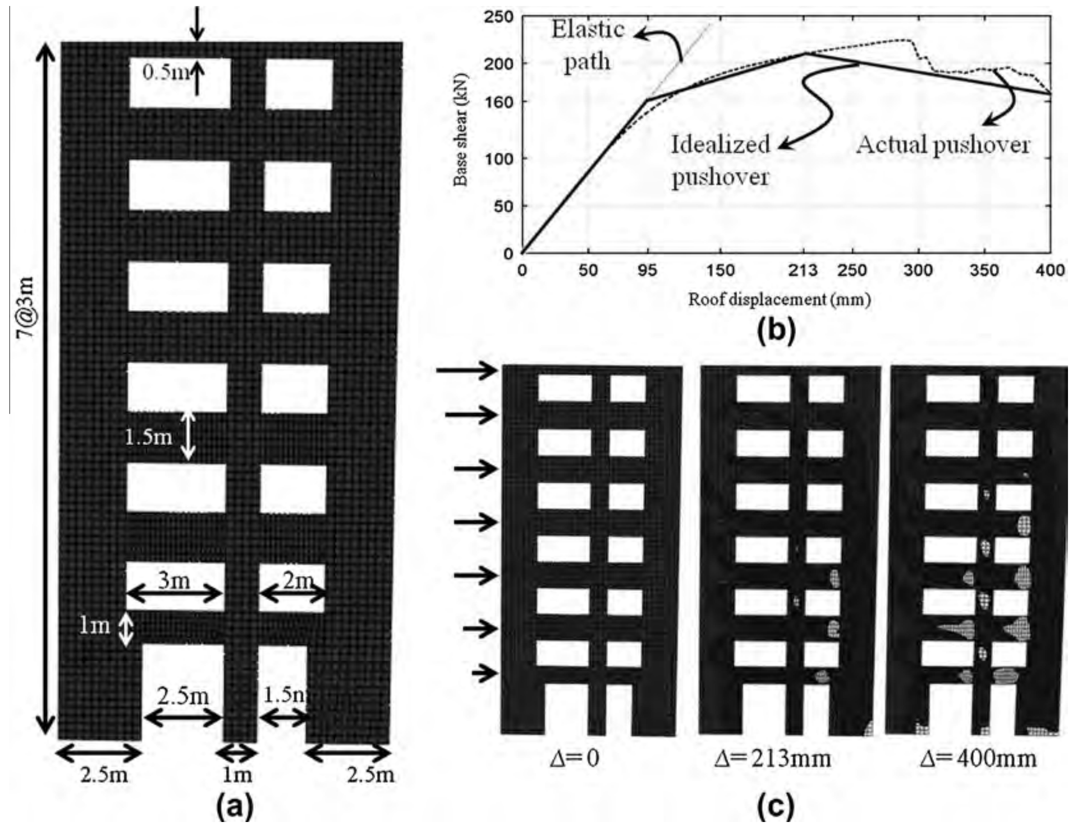


Fig. 17. (a) Building dimensions, (b) pushover curve of the building, and (c) damage states of the building, Δ stands for roof displacement.

strength degradation in most concrete element would start by concrete crushing or reinforcement rupture. It should be clarified that reinforcement buckling would not occur before concrete crushing and spalling.

In order to achieve this goal, principal strains of the JK wall are limited both in compression and tension. There is no need to impose additional limitation on shear strains as according to strut and tie technique, every shear dominated element can be modeled with some compression-only and tension-only components. The first row of the table prevents concrete crushing and subsequent buckling of reinforcements and the second row is considered to avoid tensile fracture of JK panel and steel rebars. These strains are engineering strains however true or logarithmic strains can also be used instead of them. Moreover, strain-based criteria for immediate occupancy (IO) level are selected to be 40% of the LS performance. This value is selected based upon engineering judgment and also ratios of the IO to LS criteria for shear wall components which have been adopted by FEMA 356 [26].

The proposed acceptance criteria are reported only for primary components as in the JK system virtually all components are primary.

6.2. Development length

Development length of all plain reinforcements is supposed to be provided according to bearing capacity of the EPS concrete and all bond strengths between plain reinforcements and EPS concrete should be neglected. For example in the case of JK stiffener, the bonding strength is provided by the bearing stress that diagonal elements impose on the EPS concrete. Therefore, net-shaped reinforcements, such as JK panel and JK stiffener, are more preferable in the case of EPS concrete. At the experimental program, according to the provided embedment length for the vertical JK stiffeners, only about 100 MPa can be developed in these elements while their ultimate capacity is about 740 MPa. This important feature should be implicitly considered during the nonlinear analysis by assigning lower capacities for elements which have not fully embedded. Moreover, development length of deformed rebars should be provided using a standard hook or a large embedment length according to current codes of practice.

Table 9
Proposed acceptance criteria for JK system.

	IO	LS	CP
Principal compressive strain	0.003	0.007	0.01
Principal tensile strain	0.02	0.05	0.08

7. Conclusions

A new structural system called JK system which uses JK walls as its primarily structural elements was introduced and its behavior under lateral loads was experimentally and numerically investigated. The main findings of this study are categorized into the following three parts.

7.1. EPS concrete

The used EPS concrete has a low strength and a low elastic modulus due to absence of aggregates. The concrete can sustain large strains both in tension and compression within its elastic region. In contrast with high strength concretes, the EPS concrete does not experience any sudden explosive failure in compression. Besides, it needs low amount of thermal-shrinkage reinforcements because of its low modulus of elasticity. It is more preferable to reinforce such a low strength concrete through net-shaped reinforcements, such as JK panel and JK stiffener, rather than straight rebars. Moreover, it is more suitable to use reinforcements with small cross sections in order to reduce required development lengths.

7.2. JK wall

It was found that JK walls can sustain large ductility demands as well as acceptable stiffness and strength degradations. JK panel provides virtually a one-way reinforcement for the JK wall while the perpendicular reinforcement would be provided by JK stiffeners and additional rebars. During the tests, JK stiffeners experienced no rupture or buckling, in contrast with JK panel strips. The main reason of such behavior is the fact that JK stiffeners need relatively large embedment lengths to develop their full capacities, greater than those provided in the tested specimens. It was also found that the required development length should be calculated according to bearing capacity at the reinforcement/EPS concrete interface. It is well-understood that EPS concrete tends to localize its damages. This behavior was again observed during this study such that most damages occurred at the lower 50 cm of the specimens. Using a simplified equivalent technique, JK wall can be simply modeled by conventional analytical software for practical design purposes. The results indicate that JK wall while has been constructed with low strength EPS concrete, behaves very similar to conventional concrete shear walls in terms of shape of the cyclic loops, stiffness degradation, ductility, etc. According to obtained results, some strain-based acceptance criteria were proposed for the JK wall such that the wall can be designed according to performance based philosophy.

7.3. JK system

JK system is a new lightweight structural system in which all gravity and lateral loads would be supported by JK walls. In this system all walls are structural elements which provide a high level of redundancy such that there are many load paths for both gravity and lateral loads. Because of lightness of the used EPS concrete, the system is quite lightweight and is suitable for seismic-prone regions. Efficiency of the JK system is examined for a 7-story residential building. Moreover, using both experimental and numerical results, some design considerations are proposed for the system including related performance criteria. According to obtained results, JK system seems to be comparable with other structural systems. However, the authors would like to elaborate that the main focus of the current study was about behavior of isolated JK walls and more research is still required to cover behavior of the JK system as a complete structural system. Finally, the authors would like to elaborate that the introduced JK system is in an early state of development and at this time, JK system for tall or medium buildings are discouraged due to the lack of thorough understanding about its strength and service level performances. Therefore, for a better understanding, more numerical, experimental, and case studies in this field are welcome.

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