Ενίσχυση τοιχοπληρώσεων με ανοίγματα εμφατνούμενων σε πλαίσια ΟΣ με Μανδύες Ινοπλεγμάτων σε Ανόργανη Μήτρα (TRM)

Χριστιάνα Φιλίππου, Νικόλας Κυριακίδης, Κρίστης Χρυσοστόμου

ΠΕΡΙΛΗΨΗ

Την τελευταία δεκαετία έχει γίνει εκτενής έρευνα σχετικά με την ενίσχυση τοιχοπληρώσεων εμφατνούμενων σε πλαίσια οπλισμένου σκυροδέματος (ΟΣ) χρησιμοποιώντας εξωτερικό οπλισμό ινοπλεγμάτων μέσα σε μανδύα κονιάματος τσιμεντοειδούς βάσης (TRM). Αντικείμενο της παρούσας εργασίας είναι η αναλυτική διερεύνηση της συμπεριφοράς ενισχυμένων με TRM τοιχοπληρωμένων πλαίσιων ΟΣ με κεντρικά ανοίγματα υπό εντός επιπέδου ανακυκλιζόμενη φόρτιση. Αυτή η μελέτη βασίζεται στην βαθμονόμηση-επαλήθευση του αναπτυχθέντος προσομοίωματος με τα αποτελέσματα των πειραματικών δοκιμών. Αρχικά αναπτύχθηκε αναλυτικό προσομοίωμα το οποίο βασίστηκε στην χρήση πεπερασμένων στοιχείων στο λογισμικό DIANA για την προσομοίωση της απόκρισης των μη ενισχυμένων και ενισχυμένων τοιχοπληρώσεων εμφατνούμενων σε πλαίσια (ΟΣ) υπό εντός επιπέδου ανακυκλιζόμενη φόρτιση. Μετά την επαλήθευση των αναλυτικών προσομείων, αριθμητικές αναλύσεις πραγματοποιήθηκαν αφενός για να μελετήσουν την επιρροή του μεγέθους των κεντρικών ανοίγματων στην συμπεριφορά των μη ενισχυμένων τοιχοπληρωμένων πλαίσιων ΟΣ υπό εντός επιπέδου φόρτιση και αφετέρου για την διερεύνηση της αποδοτικότητας της νέας τεχνικής ενίσχυσης TRM στις τοιχοπληρώσεις με ανοίγματα εμφατνούμενες σε πλαίσια (ΟΣ). Συμφωνώ μαζί με τα αποτελέσματα της αναλυτικής διερεύνησης προέκυψε ότι η νέα τεχνική ενίσχυσης είναι εξαιρετικά υποσχόμενη αφού με την χρήση TRM επιτυγχάνεται σημαντική αύξηση στην πλευρική αντίσταση, στην δυσκαμψία αλλά και στην απορρόφηση ενέργειας των τοιχοπληρώσεων με ανοίγματα εμφατνούμενων σε πλαίσια ΟΣ.
Seismic retrofitting of masonry-infilled RC frame with openings using TRM

C.A.Filippou¹, N.Kyriakides², C.Z.Chrysostomou³

ABSTRACT

The effectiveness of textile reinforced mortar (TRM) strengthening technique on the in-plane behaviour on masonry-infilled reinforced concrete (RC) frame with central opening under cyclic loading is investigated. First, a finite element model of the masonry-infilled RC frame with and without TRM is developed using DIANA software. Then, after calibration with experimental results, a numerical study is carried out to examine the effect of the presence of different size of central opening on the behaviour of masonry-infilled RC frame. Finally, a numerical study is performed in order to investigate the influence of TRM in the behaviour of masonry-infilled RC frames with different size of central openings subjected to in-plane cyclic loading. The results show that the lateral capacity, stiffness and the hysteric energy of masonry-infilled RC frame decreases as the opening area increases. Further, the lateral capacity, the stiffness and the hysteric energy of TRM strengthened masonry-infilled RC frames with openings was found to be significantly higher than those of unstrengthened one and had much more ductile performance.

1 INTRODUCTION

The behaviour of masonry-infilled reinforced concrete (RC) frame structures during an earthquake has attracted the attention of structural engineers since 1950’s. Several experimental studies have been carried out to examine the behaviour of masonry-infilled RC frame under earthquake loading [1–4]. Previous studies have been carried out aiming at investigating the influence of openings and their position on the in-plane behaviour of masonry-infilled RC frames both experimentally [5–8] and numerically [9–14]. Liaw (1972) [14] performed an analytical study to investigate the effect of the size of the opening on the stiffness of the infilled RC frame. The results show that a central opening of size 20-30% of the panel area reduces the stiffness by

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about 70-80%. Asteris (2003) and Kakaletsis and Karayannis (2009) both show that the higher value of stiffness reduction of the infilled frames appears when the opening is upon diagonal [15,16]. Decanini et al. (2012) found that the opening located in the corner of the panel may have created unfavorable effects like short column in the frame (Figure 1a)[17]. Recently, numerical models were developed using the DIANA software in order to simulate the behavior of masonry-infilled RC frame with openings [18–21]. The results show that the failure model and the crack pattern predicted by the nonlinear finite element analysis were in good agreement with those obtained by experimental observations. Authors suggested that further work is required in order to properly define the initial stiffness of the wall.

Seismic rehabilitation of existing structural or non-structural elements is a changing problem nowadays. Several retrofitting techniques have been proposed in order to increase the strength, stiffness, deformation capacity and the ductility of masonry-infilled RC frame structures [23,24]. The recent retrofitting techniques include the use of fiber reinforced polymers (FRP) [25–28], ductile-fiber-reinforced cementitious composites (FRCM) [29,30] and textile reinforced mortar (TRM) [31–33]. TRM jacketing is an extremely promising solution for the strengthening of unreinforced infill subjected to either out-of-plane or in-plane load [34–36]. Whereas significant research has been conducted and reported for strengthening solid masonry infill, much less has been carried out for retrofitting infill wall with openings [37–39]. The present study examines the effect of an opening on the behaviour of masonry-infilled RC frames and the effectiveness of the TRM strengthening technique on the masonry-infilled RC frame with openings. The masonry infilled model was calibrated based on the experimental results of a 2/3 scaled three story masonry-infilled RC frame. First, a finite element (FE) model of masonry-infilled RC frame with and without TRM was developed using DIANA software. Then, after calibration with experimental results, a numerical study is carried out to investigate the effect of the presence of different size of central openings on the in-plane cyclic behaviour of masonry-infilled RC frames. Finally, a numerical study performed in order to investigate the effectiveness of TRM on the behaviour of the masonry-infilled RC frame with different size of central openings under in-plane cyclic loading.
2 BRIEF OVERVIEW OF THE EXPERIMENTAL CASE STUDY

In the experimental case-study carried out by Koutas et al. (2014) the effectiveness of seismic retrofitting of existing masonry-infilled RC frame with TRM was studied [32]. In this part, a short description of the experimental case-study is presented for the benefit of the reader.

The geometry of the masonry-infilled RC frame is shown in Figure 2a. For beams and columns C25/30 class concrete was used, with the mean value of compressive strength of concrete equal to 27.8 MPa. The modulus of elasticity of the concrete was 24.1 GPa. The longitudinal column ribbed reinforcement was class B500C, 12 mm diameter. The transverse reinforcement for all concrete members was class of S220, 6 mm diameter smooth steel stirrups. The infill wall had length-to-height aspect ratio 1.36. The compressive strength of masonry was 501 MPa and the elastic modulus of the masonry perpendicular to the bed joints was 3.37 GPa. In addition, the mean value of diagonal crackling stress was 0.39 MPa and the shear modulus was 1.38 GPa. The wall was supported rigidly by the RC foundation beam plate at the bottom of the frame.

![Figure 2a](image1.png)  
(a) Geometry of the masonry-infilled RC frame.

![Figure 2b](image2.png)  
(b) Strengthening scheme: textile anchors of and TRM layer on the faces of the masonry infill.

![Figure 2c](image3.png)  
(c) Test set up [32]

The strengthening scheme for masonry-infilled RC frame is shown in Figure 2b. The strengthening scheme incudes: carbon-TRM fully wrapped at the ends of columns at the first and second stories, glass-TRM externally bonded on the face of the infill walls and in total 11 and 8 anchors per side were placed at equal spaces along the interfaces (Figure 2b). The mortar used as the binding material of the textile was a commercial fiber-reinforced cement-based mortar. The mean values of the compressive and flexural strength were equal to 18.9 and 4.3 MPa, respectively. Figure 2c shows the general view of the test set up. Prestressing robs were used on the foundation beam and the gravity load with value of 80 kN per story was considered. The maximum base-shear forced was attained during the third and fourth cycle of loading for the unretrofitted and retrofitted specimen respectively. After the fourth cycle of loading in the retrofitted specimen the lateral strength was decreasing due to complete debonding of the TRM from the beam surface on the back side of the first story and due to local crushing at the first story infilled at the two upper ends of the columns.
3. VALIDATION OF THE NUMERICAL MODEL

This study used DIANA finite element analysis software [40] to model the masonry-infilled RC frame with and without TRM. The calibration of the numerical models was based on the experimental test conducted by Koutas et al. (2014) [32].

3.1. Finite element modelling of masonry-infilled RC frame with and without TRM

Finite element modelling consists of the selection of the element type, geometry, size of meshing, boundary constrains, loading sequence and the selection of appropriate material models (assign the material properties) to simulate the masonry-infilled RC frame with and without TRM. Full details about the numerical modelling of masonry-infilled RC frame can be found in Filippou et al. (2019)[41].

The concrete frame, masonry infill and TRM were modelled with eight-node quadrilateral isoperimetric plane stress elements (CQ16M). The steel reinforcement in the frame was modelled with two-node bar element and it were connected to the eight-node concrete element at the two external nodes. The interface between the infill all and the frame was modelled by the three-point line interface element (CL121) capable of modelling cohesion, separation and cyclic behaviour of the interaction between wall and frame. The glass and carbon-TRM elements were considered to be fully bonded to the infill wall and concrete elements, respectively, since no deponding was observed during the experiment. In order to model the strong foundation beam that was used in the experimental case-study, all nodes at the base of the model were restrained by preventing any translation in the x and y-direction. The models were loaded with constant axial load (174KN/mm) on the top of each column in order to simulate the dead load of the structure. The loading process during the numerical model was simulated as closely as possible to the experimental loading using point prescribed deformation load at the top of each floor.

The concrete material model that was chosen is the Total Strain Crack model [42]. The Total Strain based Crack model describes the tensile and compressive behaviour of concrete without taking into account the stress confinement effect, as shown in Figure 3. Besides the definition of the basic properties like Young’s modulus, the Total Strain Crack model required only a small number of engineering parameters such as the tensile (2.15MPa) and the compressive strength (27.2MPa) based on the Maekawa Fukuura model (Maekawa 2016) and the fracture energy in tension (130N/m).This model has no ability to reduce the stiffness due to early cracking of the concrete section and therefore the modulus of elasticity (9.1 GPa) was reduced.

The Menegotto-Pinto model (Maekawa 2016) was chosen for the cyclic behaviour of steel reinforcement. It consists of a stress-strain relationship branches between two subsequent reversal point and the parameters involved are updated after each load reversal. The modulus of elasticity was 406GPa, and the yield stress was 549MPa and 295MPa for longitudinal reinforcement and stirrups respectively.
An interface gap model, plasticity based and proposed by Lourenco and Rots [44,45] was used for the interface elements describing the connection between the masonry infill wall and the bounding RC frame. The model includes a tension cut-off for tensile failure (mode I), a Coulomb friction envelope for shear failure (mode II) and a gap model for compressive failure. The interfaces normal modulus was 6KN/mm³ and 3 KN/mm³ for perpendicular (y-direction) and longitudinal (x-direction) direction, respectively. The interface shear modulus was 0.06 KN/mm³ and 0.03 KN/mm³ for y-direction and x-direction, respectively.

Table 1. Mechanical properties of engineering masonry model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic parameters</td>
<td></td>
</tr>
<tr>
<td>Modulus of elasticity X-direction (GPa)</td>
<td>7</td>
</tr>
<tr>
<td>Modulus of elasticity Y-direction (GPa)</td>
<td>3.37</td>
</tr>
<tr>
<td>Shear modulus (GPa)</td>
<td>1.38</td>
</tr>
<tr>
<td>Mass density (Kg/m³)</td>
<td>800</td>
</tr>
<tr>
<td>Cracking: head joint failure</td>
<td></td>
</tr>
<tr>
<td>Tensile strength normal to the bed joint (MPa)</td>
<td>0.5</td>
</tr>
<tr>
<td>Residual tensile strength (MPa)</td>
<td>0.2</td>
</tr>
<tr>
<td>Fracture energy in tension (N/mm)</td>
<td>0.05</td>
</tr>
<tr>
<td>Crushing parameters</td>
<td></td>
</tr>
<tr>
<td>Compressive strength (MPa) (Rots 2017)</td>
<td>5.1</td>
</tr>
<tr>
<td>Fracture energy in compression (N/mm)</td>
<td>40</td>
</tr>
<tr>
<td>Shear failure parameters</td>
<td></td>
</tr>
<tr>
<td>Cohesion (MPa) (Cur 1994)</td>
<td>0.71</td>
</tr>
<tr>
<td>Shear fracture energy (N/mm) [46]</td>
<td>1</td>
</tr>
<tr>
<td>Friction angle (degree) [46]</td>
<td>20</td>
</tr>
</tbody>
</table>

The masonry infill material model that was chosen, is the Engineering Masonry model [47] which is a smeared failure model and it has a total-strain based continuum model that covers tensile, shear and compression failure modes. The engineering masonry model requires a large number of engineering parameters and most of these parameters were not measured in the experimental case-study. The direct input parameters that are necessary to apply the Engineering masonry model as implemented in the DIANA software are shown in Table 1. These material parameters were taken from the literature, for example the compressive fracture energy and the tensile energy were calculated according to Rots (2017) [47]. In addition, the cohesion was obtained 1.5 times greater than that of tensile strength according to the relation that was proposed by Cur (1994)[48].
The TRM material model that was chosen is the Total Strain crack model with Fiber Reinforced Concrete model \( (\text{fib}) \) for tensile behaviour [49]. The \( \text{fib} \) Model Code for concrete Structure 2010 model was chosen for the compressive behaviour of the TRM. Besides the definition of basic properties, like Young’s modulus, the total strain crack model requires input parameters for the composite material behaviour in tension and compression. Fiber reinforced concrete model \( (\text{fib}) \) was specified as a function of the total strain.

3.2. Validation and analysis

Nonlinear cyclic analysis (deformation control) was performed for the masonry-infield RC frame with and without TRM. A comparison of the base-shear top-floor displacement obtained during the experimental (black line) and numerical analysis (red line) of masonry-infilled RC frame without and with TRM are shown in Figure 4a and 4b, respectively.

From Figure 4a and 4b it is apparent that there is a good agreement between the numerical and experimental results for masonry-infilled RC frame without and with strengthening material TRM regarding the initial stiffness, ultimate stiffness, shear capacity and energy absorption in a cycle of loading and unloading. A discrepancy appears in the last cycle of loading, in which for both cases the shear force capacity and the energy absorption (area enclosed in the loop in the base-shear versus displacement curve) are overestimated compared to the experimental results, which may be attributed to high nonlinearities introduced at that stage during the experiment (soft-story failure of the ground floor wall).

3 PARAMETRIC STUDY
The parametric study aims to evaluate the behaviour of masonry-infilled walls with different size of opening with and without strengthening material TRM under in-plane cyclic loading. This section is divided in two parts: (1) assessment of the influence of the percentage of a central window opening on the behaviour of masonry-infilled RC frame and (2) the effectiveness of TRM strengthening technique on the behaviour of masonry-infilled RC frame with openings. The behaviour of masonry-infilled RC frame with openings and the behaviour of TRM strengthened masonry-infilled RC frame with openings under cyclic loading were investigated using calibrated finite element models as a described in previous section. Therefore, in this study a nonlinear finite element models have been developed for masonry-infilled RC frame with different size of central opening (Figure 5a) without and with strengthening material TRM using the DIANA software. For these numerical models, the material models and the mechanical properties, the type of elements, mesh, loading, boundary condition and the type of analysis were the same as those considered in the calibrated models. In these models, as shown in the Figure 5b a lintel-beam made of plain concrete was modelled in the upper part of the window.

Based on the literature, the location of the opening in this study it was decided to be at the centre of the infill wall so that the opening is upon diagonal, as shown in Figure 8a. Based on the literature review, the area of the central opening was defined as shown in the Table 2. The notation of the model specimen is SO (%) where the O and S denote the unstrengthened and strengthened specimen, respectively and the percentage denotes the percentage ratio of the opening area to infill wall area. The variation of the central opening was selected to be as close as possible to the experiments conducted in the past [18,50–52] in order to be able to compare the results.

Table 2. Geometric characterization of the openings

<table>
<thead>
<tr>
<th>Model name without TRM</th>
<th>Model name with TRM</th>
<th>Length of opening (L)</th>
<th>Height of opening (H)</th>
<th>Length of infill</th>
<th>Height of infill</th>
<th>Percentage ratio of opening area to infill area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O (0%) S0 (0%)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>2270</td>
<td>1670</td>
<td>0</td>
</tr>
<tr>
<td>O (5%) S0 (5%)</td>
<td></td>
<td>454</td>
<td>445</td>
<td>2270</td>
<td>1670</td>
<td>5</td>
</tr>
<tr>
<td>O (8%) S0 (8%)</td>
<td></td>
<td>681</td>
<td>445</td>
<td>2270</td>
<td>1670</td>
<td>8</td>
</tr>
<tr>
<td>O (12%) S0 (12%)</td>
<td></td>
<td>681</td>
<td>668</td>
<td>2270</td>
<td>1670</td>
<td>12</td>
</tr>
<tr>
<td>O (16%) S0 (16%)</td>
<td></td>
<td>908</td>
<td>668</td>
<td>2270</td>
<td>1670</td>
<td>16</td>
</tr>
<tr>
<td>O (20%) S0 (20%)</td>
<td></td>
<td>1135</td>
<td>668</td>
<td>2270</td>
<td>1670</td>
<td>20</td>
</tr>
<tr>
<td>O (27%) S0 (27%)</td>
<td></td>
<td>1362</td>
<td>780</td>
<td>2270</td>
<td>1670</td>
<td>27</td>
</tr>
<tr>
<td>O (100%) S0 (100%)</td>
<td></td>
<td>2270</td>
<td>1670</td>
<td>2270</td>
<td>1670</td>
<td>100</td>
</tr>
</tbody>
</table>
4.1. Influence of opening on the behaviour of masonry-infilled RC frame

In this part of the paper, the influence of a central opening and variation in its area on the in-plane behaviour of the masonry-infilled RC frame was investigated by considering different openings in the numerical model as shown in Table 2. A comparison between numerical result for different size of central opening in masonry-infilled RC frame is given in Figure 6a and b in terms of global lateral stiffness and hysteretic energy, respectively.

Based on Figure 6a and b the central opening percentage influences the lateral behavior of the three-story masonry-infilled RC frame, particularly the lateral stiffness and the hysteretic energy. It can be observed in Figure 6a that the lateral stiffness corresponding to the first three cycles of loading decreases as the opening area increases. It is also apparent the by increasing the area of the central opening by about 13-30% the hysteretic energy decreases. In the case where the opening percentage was equal to 27% the initial stiffness and the hysteretic energy decreases by 40% and 56%, respectively, compared to the wall without openings at the first cycle of loading. These observations are the same with those obtained by Mallick and Garg (1971) and Kakalestis and Karayannis (2009) [6,53]. In addition, when the central opening has size 8-16% of the masonry-infill, the energy is reduced by about 26-38% compared to the masonry without opening as it was also noted by Liaw (1979) [14]. For all cases, the lateral resistance in terms of stiffness and the hysteretic energy of masonry-infilled RC frame was from 1.15-1.6 times that of the corresponding bare frame after the third cycle of loading. Therefore, the presence of the infill walls, even with opening in all cases increased the initial stiffness of the structural system by about 2.5-6 times of the initial stiffness of the bare frame. It can be concluded that compared to the bare frame, the presence of infill walls even with openings improved the behaviour of the infilled frame.
The global results of the numerical models with openings in terms of lateral capacity (stiffness and hysteric energy), crack propagation, crack widths and shear stress distribution are satisfactory compatible with those obtained by other researchers.

4.2. TRM strengthened masonry-infilled RC frame with opening

In this part of the paper the effectiveness of TRM as a strengthening technique of masonry-infilled RC frame with central openings of different areas is presented. The variation in the area of the central opening was defined as shown in the Table 2. The strengthening scheme is the same with the masonry-infilled RC frame in the experimental case study conducted by Koutas et al. (2014).

To examine the effectiveness of TRM, the global results obtained from masonry-infilled RC frame model with central openings without (blue line) and with strengthening material TRM (red line) subjected to cyclic loading in terms of base-shear versus top-floor displacement are shown and compared in Figure 7.

![Figure 7. Base-shear versus top-floor displacement of masonry-infilled RC frame model with central openings without (dashed line) and with strengthening material TRM (solid line).](image)

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To examine the effectiveness of TRM, the global results obtained from masonry-infilled RC frame model with central openings without (blue line) and with strengthening material TRM (red line) subjected to cyclic loading in terms of base-shear versus top-floor displacement are shown and compared in Figure 7.
From the Figure 7 it can be concluded that TRM retrofit technique improves the performance of the three-story masonry-infilled RC frame with openings. The results show that the strengthened specimen has a shear capacity twice as much compared to the unstrengthened specimen for the first three cycles of loading. The maximum base shear for strengthened specimen was obtained during the fourth cycle of loading. The efficiency of strengthening is reflected by the shear force capacity of masonry-infilled RC frame with openings which increased by almost 75% during the fourth cycle of loading. The maximum base shear for central opening area equal to 5% and 8% increases about two times compared to unstrengthened one. The maximum base shear for unstrengthened specimen with opening percentage equal to 20% and 27% was 174kN and 162kN, respectively, and for strengthened specimen was 329kN and 321kN. Furthermore, strengthened specimen with small opening area (5%) behaves similarly to a strengthened specimen without opening. It is observed that the global stiffness of the TRM strengthened specimen at the maximum shear capacity increases about two times compared to the unstrengthened one. The TRM composite material improves the response of masonry-infilled RC frame in terms of lateral resistance and stiffness.

Figure 8 shows the effect of TRM strengthening in terms of hysteretic energy (ratio between energy of strengthened and unstrengthened specimen for masonry-infilled RC frame with 12% and 27% central opening area).

From the Figure 8 it can be concluded that the energy of TRM-strengthened specimen, in comparison with the reference one is 1.8-2.5 times greater. The results show that the strengthened specimen behaves in a ductile manner and dissipated a significant amount of energy compared to the unstrengthened one. Therefore, using TRM reduces the negative effect of openings on the lateral capacity and improves the performance of the masonry-infilled RC frame with openings in terms of hysteretic energy.

5. CONCLUSION

In this study, the effect of an opening on the behavior of masonry-infilled RC frame and the efficiency of TRM strengthening technique for a three-story masonry-infilled RC frame with openings was investigated using a numerical model. The model was calibrated on the
experimental results of a 2/3 scale three-story masonry infilled RC frame. The finite element model of the masonry-infilled RC frame with and without TRM was developed using the DIANA software.

The numerical results show that the central opening percentage influences the behavior of the three-story masonry-infilled RC frame, particularly its lateral stiffness and hysteric energy. In the case when the opening percentage was equal to 27% the initial stiffness and the hysteric energy decreases 40% and 56%, respectively, compared to the solid infill wall. In addition, when the central opening has size 8-16% of the masonry-infill the energy is reduced by about 26-38% compared to the solid infill wall.

A numerical study was performed in order to investigate the effectiveness of TRM on the behavior of masonry-infilled RC frame with different size of central openings under in-plane cyclic loading. It can be concluded that the TRM retrofit technique improves effectively the performance of the three-story masonry-infilled RC frame with openings. The strengthened specimen demonstrated a lateral stiffness twice as much compared to the unstrengthened specimen. It has also increased the maximum shear force capacity of masonry-infilled RC frame with openings, by almost 75%. It can be concluded that the strengthened specimen behaves in a ductile manner and dissipates a significant amount of energy compared to the unstrengthened one. Therefore, the use of TRM reduces the negative effect of openings on the lateral stiffness and improves the performance of the masonry-infilled RC frame with openings.

6. REFERENCES


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