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Analytical Study of the Behavior of Seismically Strengthened Concrete Frames Using External Shear Wall Curtains

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Abstract:

This research presents an analytical study on the behavior of concrete frames after being strengthened using an external shear wall curtain. The study is based on an experimental investigation conducted by Saleh et al. The static study demonstrated a clear consistency between the analytical and experimental findings, leading to a dynamic subsequent survey of the same model, albeit through analytical methods only. The dynamic study revealed several phenomena accompanying the interaction between the external shear wall curtain and the existing building structure. One of these phenomena was that the shear behavior of the external shear wall curtain initially attracted a significant portion of the total base shear (approximately 50%) at the beginning of seismic excitation. However, as the PGA of the seismic record was reached, the curtain wall's base shear contribution began to diminish due to the yielding of the effective anchors. This highlights the important role of anchor configuration between the frame and the curtain wall and the prescribed section of these anchors to maintain a relatively constant rate of seismic energy dissipation during an event of a damaging earthquake. In addition, the analytical results indicated that numerically modeling an anchor as a truss element yields better results than an element with beam cross-section behavior. This raises questions about the anchor's ability to dissipate energy in tension and not compression. The anchor's behavior may not be optimal under compression, suggesting the need for further research to achieve a balanced state of energy dissipation under both tension and compression.

Keywords: Concrete Frames _ External Shear Wall Curtain _ Seismic Excitation _ Anchor Behavior _ Energy Dissipation

دراسة تحليلية لسلوك الإطارات البيتونية المدعمة زلزالياً باستخدام ستارة جدار قص خارجية

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الملخص:

تم في هذا البحث إجراء دراسة تحليلية لسلوك الإطارات البيتونية بعد تدعيمها باستخدام ستارة جدار قص خارجية، حيث بنيت هذه الدراسة على تجارب مخبرية قام بها صالح وآخرون (2010) الدراسة الاستاتيكية بينت أن التقارب بين الدراسة التحليلية والمخبرية كانت متوافقة بشكل واضح ليتم بعدها الإنتقال إلى دراسة نفس النموذج ديناميكياً ولكن بشكل تحليلي فقط. كشفت الدراسة الديناميكية بعض الظواهر المرافقة لعمل الستارة مع الهيكل القائم للبناء. منها أنّ السلوك القصي للستارة بدأ في بداية التحريض الزلزالي بجذب جزء هام من القص القاعدي الكلي (50% تقريباً) إلا أنه وبعد وصول قيمة (PGA) لذروة السجل الزلزالي بدأت مشاركة الجدار (الستارة) بالتضاؤل تدريجياً نتيجة تلدن الأنكورات الفعّالة مما يوحي بالدور الذي يلعبه تحديد أماكن تموضع هذه الأنكورات إضافة إلى تصميم مقطعها العرضي في الحفاظ على معدل شبه ثابت لتلدنها وبالتالي إمكانية تخميد الحركة الزلزالية على كامل طول فترة التحريض الزلزالي الفعّال. أيضاً بيّنت النتائج التحليلية أنّ نمذجة الأنكورات كعناصر تعمل على الشد والضغط معاً هو الأدق من ناحية النمذجة الرقميّة (الأكثر قرباً من الواقع) والذي أدّى في هذا البحث إلى الحصول على نتائج تحليليّة تقارب نتائج التجربة المخبرية للباحث صالح ورفاقه. هذا يثير تساؤلات حول قدرة الأنكورات على تبديد الطاقة الزلزالية في حالة الشد فقط دون الضغط. إذ قد لا يكون سلوك الأنكورات تحت تأثير الضغط مثالياً، الأمر الذي يستدعي إجراء المزيد من الدراسات للوصول إلى حالة متوازنة من تبديد الطاقة في حالتي الشد والضغط معاً.

الكلمات المفتاحية: الإطارات البيتونية، ستارة جدار قص خارجية، التحريض الزلزالي، سلوك الأنكورات، تبديد الطاقة.

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Context and Significance of the Study:

Reinforced concrete structures in seismic regions require adequate reinforcement to withstand lateral loads induced by earthquakes. Among the innovative engineering solutions, the external shear wall curtain technique emerges as an effective option for improving structural performance during earthquakes.

External shear walls provide an efficient solution for distributing lateral forces and reducing the frame's flexural deformations. Numerous studies have demonstrated the effectiveness of anchors in supporting shear walls and ensuring their stability during seismic excitation [2][4]. This paper aims to present a comprehensive analysis of the role of anchors in supporting shear walls and to elucidate the significance of their proper distribution in ensuring appropriate seismic response.

Ozturk's study (2010) demonstrated that an external shear wall enhances the system's stiffness and increases its resistance to earthquakes when anchors are designed judiciously. It was observed that anchors play a crucial role in ensuring the stability of the curtain under increasing loads. On the other hand, Deifalla et al. (2022) highlighted the importance of reinforcing shear walls with Glass Fiber Reinforced Polymer (GFRP) to enhance the wall's efficiency in resisting deformations caused by lateral loads, even in the presence of openings, thus increasing the effectiveness of reinforced shear walls in large structural systems

Similarly, Kotronis et al. (2005) focused on the seismic behavior of reinforced concrete walls subjected to cyclic loading, highlighting the importance of modeling the interactions between supporting elements, such as anchors, which play a crucial role in improving the response of structures exposed to repeated lateral loads. Saleh et al. (2010) investigated the performance of composite external shear walls, evaluating the wall's performance in distributing loads between the frame and the wall. However, this study did not address the role of anchors independently. This paper aims to bridge this gap by analyzing the dynamic interaction between anchors, the frame, and the curtain wall, with a focus on the ductility of anchors and its impact on the overall structural response.

Reference Experimental Study:

The experimental study conducted by Saleh et al. (2010) represents one of the key references in the field of strengthening reinforced concrete frames using external shear wall systems. In this study, a three-story single-bay reinforced concrete frame was strengthened using an external reinforced concrete shear wall connected to the existing frame through steel anchors.

The experimental program investigated the structural response of the strengthened system under cyclic lateral loading in order to simulate seismic effects. The results demonstrated that the addition of the external shear wall significantly increased the lateral stiffness and load-carrying capacity of the system. The anchors played a critical role in ensuring force transfer between the frame and the shear wall, allowing the two components to act together as a composite structural system.

The experimental results of Saleh et al. were used in the present research to calibrate the analytical model developed in ABAQUS, ensuring consistency between the numerical simulations and the observed experimental behavior.

From the review of previous studies, it can be observed that most existing research has primarily focused on the global performance of strengthened structural systems, particularly in terms of stiffness enhancement and lateral load resistance. However, limited attention has been given to the independent mechanical role of anchorage systems and their contribution to the dynamic interaction between the existing frame and the external shear wall curtain. This aspect becomes particularly important under seismic excitation, where anchor behavior under tensile forces and its ductility characteristics may significantly influence the overall structural response. Therefore, a detailed analytical investigation of anchor behavior within the strengthened system remains necessary.

Methodology:

Numerical Model Description:

The analytical model adopted the same geometric dimensions used in the reference experimental specimen. The model consisted of a single-bay, three-story reinforced concrete frame strengthened with an external shear wall curtain. According to the experimental drawings, the clear story height was 85 cm, while the beam depth was 15 cm. The cross-sectional dimensions of both columns and beams were 10 cm × 15 cm. The center-to-center distance between the two columns was 105 cm, while the clear span between the column faces was 95 cm.

The reinforced concrete frame and the external shear wall curtain were modeled using three-dimensional solid elements of type C3D8R in ABAQUS. These elements are eight-node hexahedral elements with reduced integration and are commonly used for modeling the nonlinear behavior of concrete structures.

The concrete behavior was represented using the Concrete Damaged Plasticity (CDP) model, which allows the simulation of the nonlinear response of concrete under both tension and compression while accounting for material damage evolution.

The longitudinal reinforcement and stirrups were incorporated within the concrete elements using the Embedded Region technique, which allows full interaction between the reinforcing steel and the surrounding concrete without the need to explicitly define contact interfaces.

The steel anchors were modeled using T3D2 truss elements, which transfer only axial forces (tension and compression). This modeling approach is consistent with the mechanical role of the anchors in transferring forces between the reinforced concrete frame and the external shear wall curtain.

To ensure the reliability of the numerical model, the same geometrical dimensions, material properties, and anchor distribution adopted in the reference laboratory experiment were used in the analytical model, ensuring both geometrical and mechanical consistency between the experimental and analytical representations.

Anchor Design and Properties

The connection between the existing reinforced concrete frame and the external shear wall curtain was established using chemical anchors. The anchors consisted of ribbed steel reinforcement bars with diameters of 6 mm, 8 mm, and 10 mm, manufactured from S420 structural steel. The mechanical properties of the anchor bars were verified through tensile tests conducted prior to installation. The same anchors were adopted in the numerical model, ensuring full consistency between the experimental setup and the analytical representation.

Regarding the spatial distribution, the anchors were arranged along the columns and beams at different floor levels following the configuration adopted in the laboratory experiment. For instance, in the analytical model, column anchors were distributed as one Ø10 anchor at each floor level (1Ø10). Meanwhile, beam anchors were arranged as follows: 2Ø6 at the first floor, 1Ø10 + 1Ø8 at the second floor, and 4Ø8 at the third floor.

Anchor Modeling:

Anchor modeling was carefully designed to include:

- Material Properties: Anchors were represented as elements capable of withstanding tensile forces while remaining elastic under compressive forces. This representation aims to improve the overall resistance of the structure to repeated loads.
- Spatial Distribution: Anchors were distributed in accordance with the laboratory experiment conducted by Saleh et al., to obtain results consistent with the experimental study and aid in model calibration.
- Ductility Criteria: The modeling included ductility criteria that allowed the anchors to transition from an elastic to a plastic state when subjected to high tensile forces, while remaining elastic under compression. This representation ensures that the anchors respond according to real structural behavior.
- Interaction between Anchors and Structure: The dynamic interaction between the anchors and the frame was modeled to reflect the distribution of forces during seismic excitation.
- Model Verification: For greater accuracy, the performance of the anchors was compared with experimental results, confirming a good match with the experimental reality.

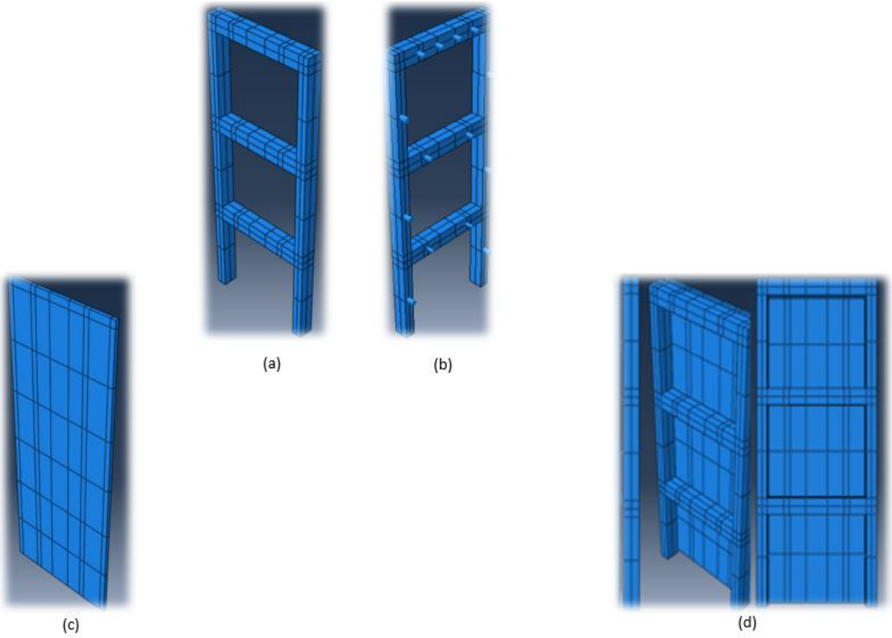


Figure (1) illustrates the analytical model of the system under study: (a) frame model, (b) anchor locations within the frame, (c) external shear wall curtain model, and (d) overall structural model.

Static Analysis: Cyclic reversed loads were applied to simulate repeated seismic loads, based on available experimental data from Saleh et al.'s study. The static analysis included the analysis of deformations and stresses resulting from these loads and their distribution between the frame and the curtain wall. This analysis helped to document the agreement between the analytical model and the experimental reality, by comparing static deformations and stress distributions between the two models. Figure 2 shows the convergence between the analytical and experimental results of Saleh et al., where the convergence reached a percentage of 91.03%. This is due to the accurate simulation of the experimental model adopted in the study.

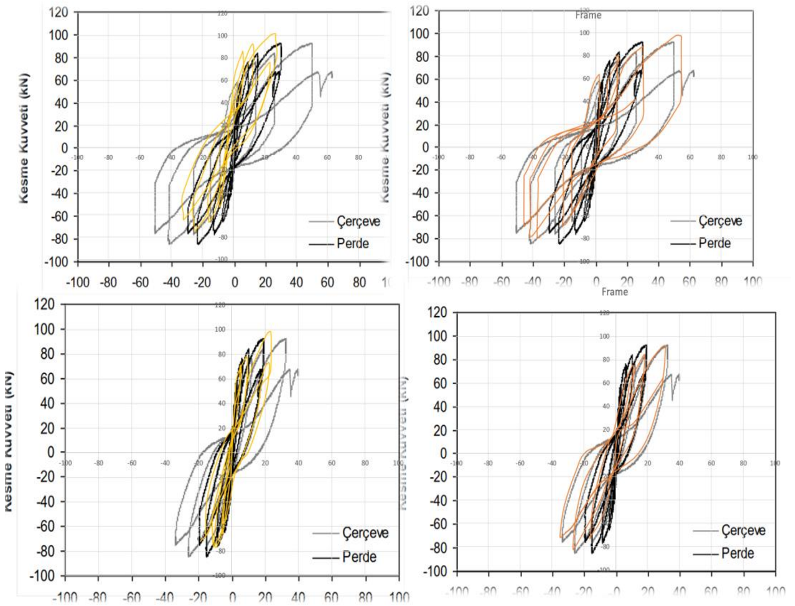


Figure (2) Comparison of hysteresis loops for both analytical and experimental models.

Dynamic Analysis: The dynamic analysis relied on a representative seismic record to analyze the time-history response of the supported model. The study highlighted the influence of the dynamic interaction between the frame and the curtain wall during seismic excitation. The analysis focused on investigating the impact of anchors and their interaction with tensile and compressive forces, with the aim of understanding the response of anchors during seismic excitation, especially at peak ground acceleration (PGA). Figure 3 presents the seismic record of the Kobe earthquake used in the study (The Kobe earthquake (1995) had a moment magnitude of 6.9 (Mw), and its ground motion record is widely used in seismic response analyses).

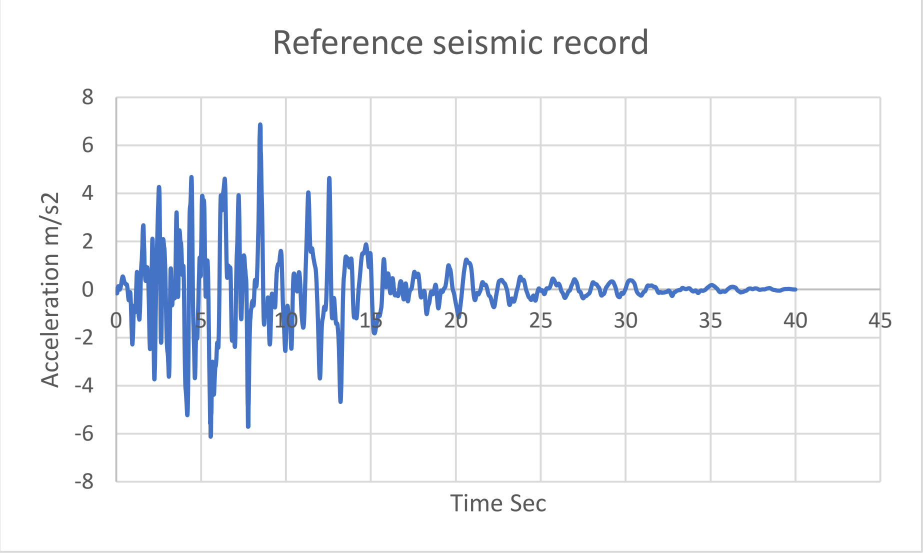


Figure (3) Adopted seismic record for the study

Model Verification: The model's stability and accuracy were verified by repeating the loading cycles three times. Each cycle was designed to match the loading cycles used in Saleh et al.'s experiments. This repetition contributed to monitoring the performance of the anchors and the structure's response under repeated loads, and documenting changes in deformations and stiffness within the model, thus confirming the stability of the analytical model. Figure 4 illustrates the model's stability under repeated loading cycles, where each column represents the increase in base shear force that the model can withstand after reinforcing the concrete frame with a concrete shear wall and connecting it to the existing structure using anchors.

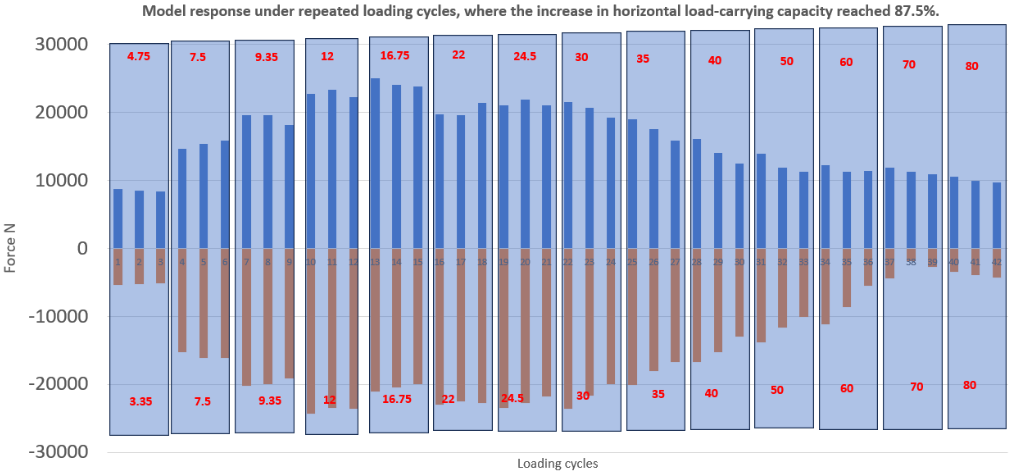


Figure (4) Model response and stability under repeated loading cycles based on Saleh et al.'s study

Results:

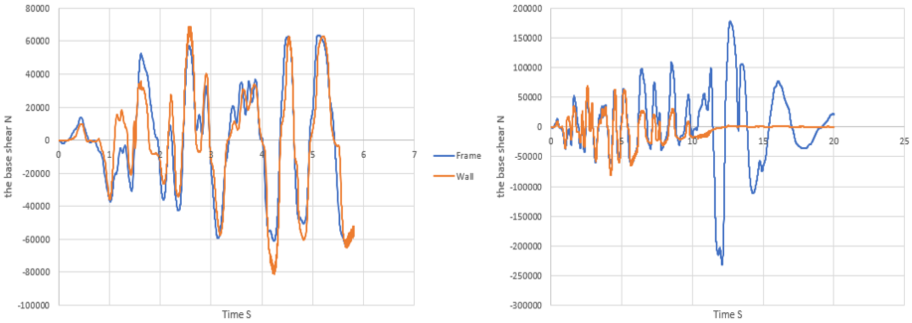
Static Results: A comparison between analytical and experimental results revealed a good agreement, where the shear wall curtain contributed to reducing deformations, improving system stiffness, and increasing the model's load-carrying capacity and resistance to horizontal loads by 87.5%. The remarkable effectiveness of the reinforced frame response to cyclic reversed loads was documented through hysteresis loops, which showed a significant improvement in the stiffness of the reinforced structure.

The obtained results indicate that the introduction of the external shear wall curtain significantly improved the overall stiffness of the structural system. This improvement is reflected in the noticeable reduction of structural deformations under cyclic loading. The strengthened frame exhibited smaller lateral displacements compared with the original configuration, indicating that the shear wall contributed effectively to resisting lateral loads. The increase in system stiffness can be attributed to the composite action developed between the existing frame and the external shear wall through the anchorage system. This interaction allowed part of the lateral forces to be transferred directly to the shear wall, reducing the flexural demand on the original frame elements.

Dynamic Results: The dynamic analysis revealed a significant interaction between the reinforced concrete frame, the external shear wall curtain, and the anchorage system during seismic excitation. At the early stage of the earthquake record, the external shear wall absorbed approximately 50% of the total base shear, indicating its effective contribution to improving the seismic performance of the strengthened system and limiting the lateral deformation of the existing frame.

As the seismic excitation progressed and the loading demand increased, several anchors began to yield primarily under tensile forces. This yielding gradually reduced the efficiency of force transfer between the frame and the shear wall, leading to a progressive decrease in the contribution of the curtain wall to resisting the applied seismic loads.

Figure 5 illustrates this interaction throughout the earthquake duration. The results show that the initial composite action between the frame and the shear wall was strong; however, as anchor yielding developed, the stiffness distribution within the structural system changed, weakening the mechanical interaction between the two components. Consequently, the overall seismic response of the strengthened structure became increasingly governed by the evolving behavior of the anchorage system.



a

b

Figure (5) Time history of energy dissipation by the curtain wall and frame for the earthquake duration of (a) 6 seconds and (b) 20 seconds

Role of Anchors: The comparison between Figure 5(a) and Figure 5(b) indicates that the role of anchors is more significant during the early stage of seismic excitation. In the short-duration response, the anchors maintain an effective mechanical connection between the reinforced concrete frame and the external shear wall curtain, allowing the two structural components to act compositely as an integrated system. However, as the seismic excitation continues and the loading demand increases, especially near and after the peak ground acceleration (PGA), some of the effective anchors begin to yield primarily under tensile forces. This progressively reduces their ability to transfer forces efficiently between the frame and the curtain wall, leading to a gradual loss of composite action at longer time intervals. In this context, the anchor cross-sectional area plays a key role, since it directly affects both the axial stiffness and the yielding capacity of the anchors. Therefore, larger anchor sections can delay yielding and preserve the interaction between the frame and the curtain wall for a longer duration of seismic excitation. Figure 6 illustrates the yielding of anchors over time, showing that the response of some anchors was delayed, and some anchors yielded before others. This phenomenon reduced the efficiency of force transfer between the concrete curtain wall and the frame.

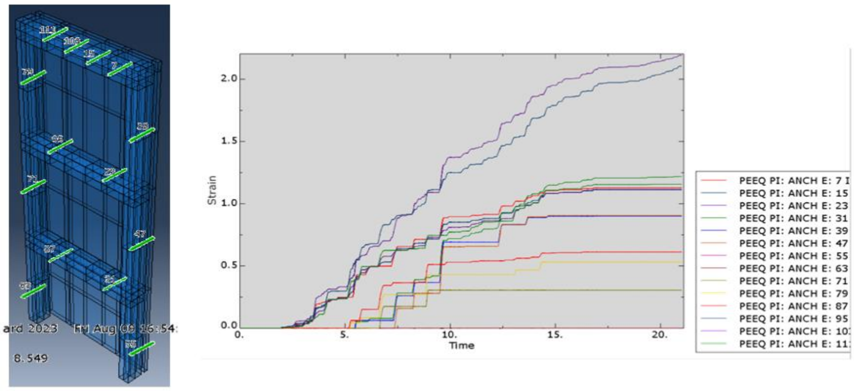


Figure (6) Evolution of anchor yielding over time

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