

Displacement-Based Design of Aluminum Shear Panels for Seismic Retrofitting of RC Buildings [†]

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Abstract

This paper presents a displacement-based design method for aluminum shear panels used in the seismic retrofit of RC buildings. The approach follows performance-based principles, directly controlling structural displacements while ensuring stable hysteretic behavior and concentrating damage in replaceable panels. The procedure links displacement demand to panel properties and geometry, enabling efficient design. A case study shows significant reductions in inter-story drift and residual deformations, improving seismic performance. The results demonstrate that aluminum shear panels are an effective and sustainable retrofit solution, offering reliable energy dissipation, easy replacement, and minimal impact on existing structures.

Keywords: aluminum shear panels; RC structures; displacement-based design; seismic retrofit

1. Introduction

A large portion of the existing reinforced concrete (RC) building stock worldwide was designed according to obsolete seismic provisions and therefore exhibits inadequate lateral stiffness, strength, and ductility. As a result, these structures are highly vulnerable to earthquake-induced damage, often experiencing significant degradation or collapse under strong ground motions. Traditional seismic design philosophies rely on the inelastic deformation of primary structural components to dissipate energy, which inherently leads to damage that may be costly or impractical to repair. Consequently, there has been a growing shift toward performance-based strategies aimed at enhancing structural resilience while limiting damage to the main load-resisting system. Among modern seismic protection techniques, the incorporation of passive energy dissipation devices has proven to be an effective and reliable solution. Metallic yielding devices have gained considerable attention due to their stable hysteretic behavior, large deformation capacity, and ease of replacement after severe seismic events. Within this category, metal shear panels (MSPs) represent a highly efficient solution, combining high initial stiffness with significant energy dissipation capabilities. Their ability to act as replaceable structural fuses makes them especially attractive for seismic retrofit applications [1]. While conventional steel-based shear panels have been extensively studied and widely implemented, increasing attention has recently been directed toward aluminum shear panels as an alternative solution. The use of aluminum alloys introduces several advantages, including reduced structural weight,



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improved corrosion resistance, and favorable cyclic performance associated with their relatively low yield strength and high ductility [2–5]. These characteristics make aluminum panels particularly suitable for retrofit interventions, where minimizing additional mass and facilitating installation are critical considerations. Despite these advantages, their application remains limited in engineering practice, primarily due to the lack of well-established and simplified design methodologies. Current design approaches for structures equipped with hysteretic dampers are often based on force-based procedures. These methods frequently neglect important aspects such as higher-mode effects, nonlinear behavior of the primary structure, and the complex interaction between the structural system and the dissipative devices [5]. In recent years, displacement-based design (DBD) methodologies have emerged as a more rational framework for seismic design, as they directly relate structural performance to deformation demands. However, their application to systems incorporating metallic dampers—particularly aluminum multi-stiffened shear panels—remains relatively underdeveloped. There is a clear need for design approaches capable of simultaneously addressing the nonlinear coupling between the primary structure and the dissipative elements, while ensuring an efficient distribution of seismic demand along the building height. In this context, the present study proposes a displacement-based design procedure for the seismic retrofit of RC frame structures using aluminum multi-stiffened shear panels. The proposed methodology explicitly accounts for the interaction between the panels and the existing structure, incorporating the nonlinear response of both components within a unified framework. The procedure is grounded in recent experimental and numerical findings on aluminum shear panels and is validated through nonlinear response-history analyses, demonstrating its effectiveness and applicability within a performance-based design framework.

2. Design of Multi-Stiffened Pure Aluminum Shear Panels

2.1. Shear Mechanism and Buckling Control in Aluminum Shear Panels

When properly designed, aluminum shear panels (ASPs) can be detailed to ensure that instability phenomena do not compromise their dissipative performance within the target deformation range. In particular, the adoption of adequate plate thickness and an optimized arrangement of longitudinal and transversal stiffeners allow delaying the onset of shear buckling well into the plastic regime [3,4]. Under these conditions, the panel response is governed predominantly by material yielding rather than instability effects. As highlighted by previous experimental and numerical studies on metal shear panels and aluminum-based solutions, appropriate stiffening strategies are essential to control both local and global buckling phenomena and to ensure stable cyclic behavior [6]. In this framework, multi-stiffened configurations represent an effective solution to prevent premature instability and to promote a more uniform stress distribution within the panel. As a result, yielding spreads progressively over the entire surface of the panel, promoting a uniform distribution of plastic strains. This behavior is essential to maximize the hysteretic energy dissipation capacity, as it prevents premature localization of deformations and avoids the degradation typically associated with buckling-driven mechanisms. Consequently, a stable and repeatable cyclic response can be achieved, characterized by wide and full hysteresis loops. Furthermore, by suppressing or postponing out-of-plane deformations up to the target displacement demand, the panel is able to develop a pure shear dissipative mechanism, in which the energy dissipation is governed by shear yielding of the material rather than by post-buckling effects. In this situation, aluminum shear panels can provide a reliable, ductile, and highly efficient source of energy dissipation within the structural system, in line with the general principles of passive control and performance-based seismic design,

and can be used according to different layouts (Figure 1). In this paper, the partial bay type configuration (Figure 1b) was considered.

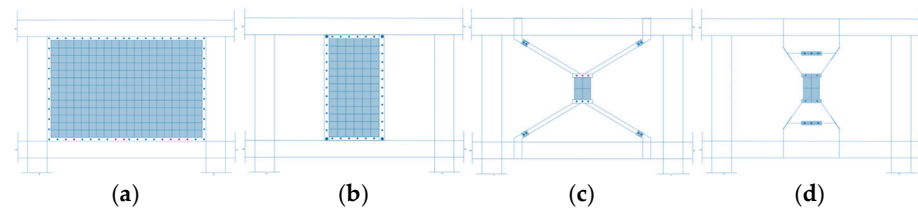


Figure 1. (a) Full bay type; (b) partial bay type; (c) bracing type; (d) pillar type.

2.2. Sizing the Aluminum Shear Panel

The design procedure generally provides the target stiffness (K^p) and strength (V^p) that are the starting point for sizing the aluminum panel. The shear panel stiffness (K^p) can be expressed according to the formulation in [7,8], where the pre-buckling shear resistance is disregarded for plates characterized by high slenderness ratios, as follows:

$$K^p = E \frac{b_w t_w}{4d} \quad (1)$$

where E is the Young's modulus of the aluminum, and b_w , t_w and d are the width, thickness, and depth of the panel (Figure 2). The shear panel strength (V^p) allows us to design its intermediate stiffeners. The factor for shear buckling (ρ_v) is defined as the normalized design shear resistance as follows [9]:

$$\rho_v = \frac{V^p}{b_w t_w f_{0.2} / \sqrt{3}} \quad (2)$$

where $f_{0.2}$ is the conventional yielding strength of the aluminum. By solving for $b_w t_w$ from Equation (1) and substituting it into Equation (2), we obtain

$$\rho_v = \frac{\sqrt{3}}{4} \cdot \frac{E}{f_{0.2}} \cdot \frac{V^p}{K^p d} \quad (3)$$

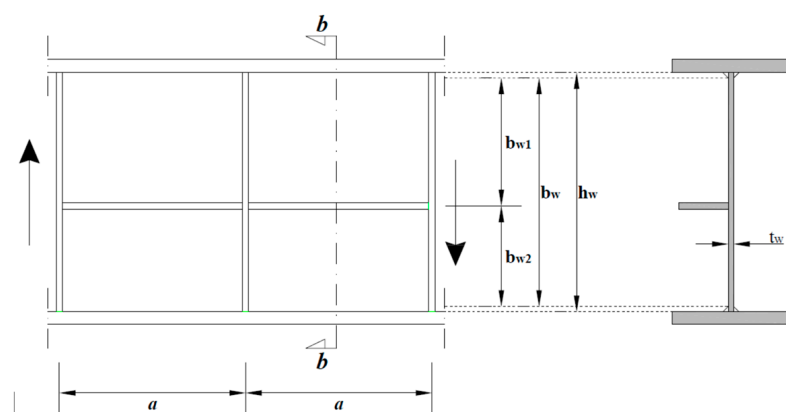


Figure 2. Full web with transverse and longitudinal stiffeners.

The value of ρ_v is subsequently employed to determine the spacing of longitudinal and transverse web stiffeners, ensuring that the yield strength remains lower than the

elastic buckling strength. To achieve this, the shear buckling factor ρ_v is formulated as a function of the slenderness parameter, as shown below [10]:

$$\begin{aligned}
 \lambda_w &< \frac{0.48}{\eta} \\
 \frac{0.48}{\eta} &< \lambda_w < 0.95 \\
 0.95 &< \lambda_w < 2.29 \\
 \lambda_w &> 2.29 \\
 \rho_v &= \eta \\
 \rho_v &= \frac{2.774}{\lambda_w^{0.2175}} \\
 \rho_v &= \frac{2.8163}{\lambda_w^{0.1047}} \\
 \rho_v &= \frac{2.6176}{\lambda_w^{0.0122}}
 \end{aligned} \tag{4}$$

where η depends on the hardening ratio (f_{aw}/f_{0w}) as follows:

$$\eta = 0.7 + 0.35f_{aw}/f_{0w} \tag{5}$$

And the slenderness parameter (λ_w) is given by:

$$\lambda_w = \sqrt{\frac{f_v}{\tau_{cr}}} = \frac{0.81}{\sqrt{k_\tau}} \cdot \frac{a}{t_w} \cdot \sqrt{\frac{f_{0.2}}{E}} \tag{6}$$

where f_v is the yielding shear strength of the aluminum, τ_{cr} is the Eulerian shear buckling stress, a is the spacing of the intermediate stiffeners (Figure 2), and k_τ is the shear buckling coefficient that for squared subpanels and rigid stiffeners is given by [10]:

$$k_\tau = 4.00 + 5.34 \cdot \left(\frac{b_w}{a}\right)^2 + 9.00 \cdot \left(\frac{b_w}{a}\right)^2 \cdot \left(\frac{I_{st}}{t_w^3 \cdot b_w}\right)^{\frac{3}{4}} \tag{7}$$

In Equation (7) I_{st} represents the total second moment of area contributed by all longitudinal stiffeners, where each stiffener is assumed to collaborate with an effective width of $15t_w$.

An iterative (trial-and-error) approach is required to identify the appropriate stiffener spacing such that the resulting value of ρ_v computed from Equation (4) matches the design requirement prescribed by Equation (3). Finally, the second moment of inertia of the stiffener ribs must be verified to ensure that it is sufficiently large to prevent global buckling of the shear panel, which may otherwise occur due to its limited out-of-plane flexural stiffness. To check this, the minimum rib inertia needed to avoid global buckling is evaluated using the following expression [10]:

$$\begin{aligned}
 \gamma &= \frac{0.1}{\lambda_{w,1}^2} \\
 \gamma &= \frac{I_{st}}{t_w b_w} \\
 \lambda_{w,1} &= 0.35 \cdot \frac{a}{t_w} \cdot \sqrt{\frac{f_{0.2}}{E}}
 \end{aligned} \tag{8}$$

3. Aluminum Shear Panels as a Retrofit Solution for RC Buildings

3.1. Dual System Decomposition

The addition of metal shear panels transforms the original RC structure into a dual system in which both the frame and the panels contribute to the overall seismic response.

Unlike simplified approaches, the proposed method accounts for the inelastic behavior of the RC structure, which may crack and yield even at low drift levels. Moreover, the mechanical interaction between the frame and the shear panels is explicitly considered, leading to a more accurate representation of the structural response. The retrofitted structure is modeled as a dual system, where the RC frame and ASPs interact to resist seismic loads. To evaluate the seismic capacity, a pushover analysis should be performed on the dual system. However, the geometrical and mechanical properties of the ASPs are initially unknown. Therefore, an iterative procedure is applied. At the first step, the pushover analysis of the existing structure is carried out. In the subsequent steps, a pushover analysis of the retrofitted structure is performed, and the i -th story shear is expressed as the sum of the contributions of the frame and the aluminum shear panels (i.e., $V_i = V_i^f + V_i^p$), consistent with the conceptual decomposition of the structural system into two interacting subsystems: the RC frame system and the shear panel system (Figure 3). As an example, Figure 4 shows a 6-story reinforced concrete framed building regular in both plan and elevation designed for a gravity load beam span of 5.0 m and an inter-story height of 3.0 m. Figure 5 shows the story shear–drift curves of the building in the X- and Y-direction. These curves are then idealized using the well-known trilinear Takeda model and assuming a uniform yield drift along the height:

$$\delta_y^f = \sum_{i=1}^N \delta_{y,i}^f / N \quad (9)$$

where $\delta_{y,i}^f$ is the i -th story yield drift and N is the number of the stories of the building. Assuming the same target drift capacity (δ_t^f) and ductility ratio ($\mu_f = \delta_t^f / \delta_y^f$) gives the trilinear idealized curves of Figure 6.

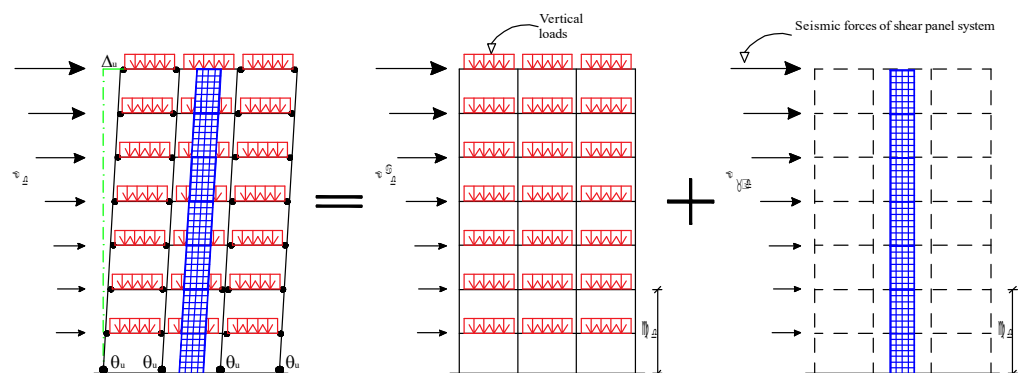


Figure 3. Retrofitted system (Total structural system) decomposed in two subsystems in parallel (Frame system + Shearpanel system).

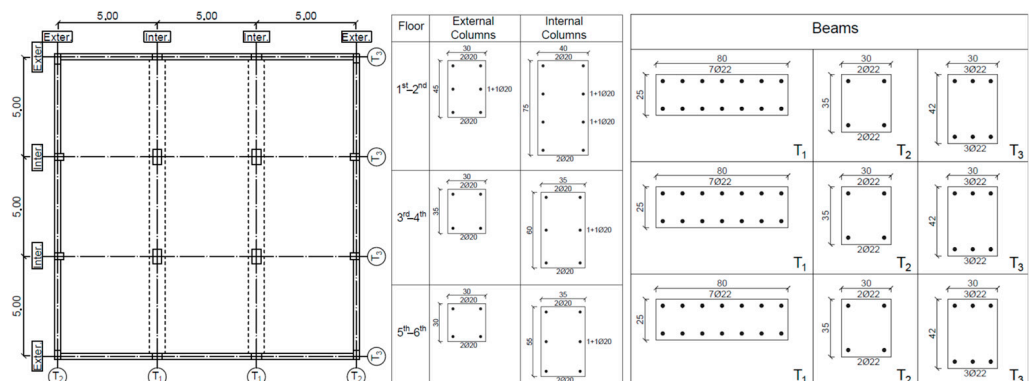


Figure 4. Plan view and details of the case-study building.

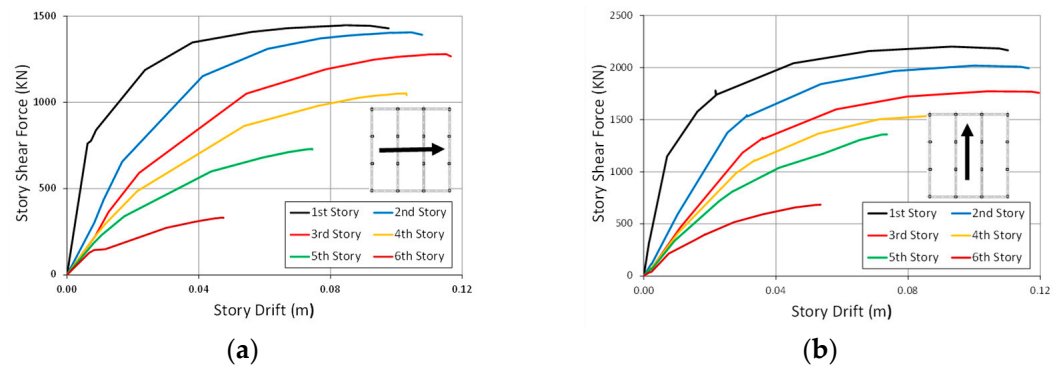


Figure 5. Story pushover curves: (a) X-direction; (b) Y-direction.

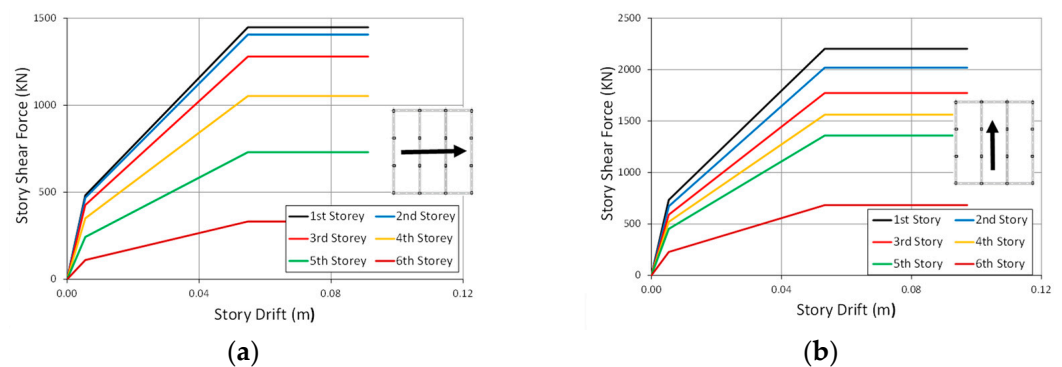


Figure 6. Idealized trilinear model of pushover curves: (a) X-direction; (b) Y-direction.

3.2. SDOF Idealization of the Main Structure

The as-built structure is reduced to an equivalent SDOF model based on the first vibration mode. The effective height (h_{eq}) and mass (m_{eq}) are computed as

$$h_{eq} = \frac{\sum_{i=1}^N (m_i \phi_i h_i)}{\sum_{i=1}^N (m_i \phi_i)} \quad (10)$$

$$m_{eq} = \frac{\sum_{i=1}^N (m_i \phi_i)^2}{\sum_{i=1}^N (m_i \phi_i)}$$

where m_i , ϕ_i and h_i are the mass, modal displacement, and height of the i -th story.

The secant period (T_μ^f) of the system is defined from the first-mode period (T^f) and the ratio between secant (K_μ^f) and initial (K_0^f) stiffness:

$$T_\mu^f = T^f \sqrt{\frac{K_0^f}{K_\mu^f}} = T^f \sqrt{\frac{K_0^f}{\alpha_y K_0^f / \mu_f}} = T^f \sqrt{\frac{\mu_f}{\alpha_y}} \quad (11)$$

The drift demand (θ_d^f) is evaluated using the response spectrum:

$$\theta_d^f = \frac{S_D(T_\mu^f; \xi_0^f)}{h_{eq}} \cong \frac{1}{h_{eq}} \cdot S_A(T_\mu^f; \xi_0^f) \left(\frac{T^f}{2\pi} \right)^2 \quad (12)$$

where S_D and S_A are the spectral displacement and acceleration, and ξ_0^f is the damping ratio. The drift capacity is instead defined as $\theta_t^f = \delta_t^f / h_{eq}$. Finally, the ratio between capacity and demand defines the drift reduction factor $R_p = \theta_t^f / \theta_d^f$.

3.3. SDOF Idealization of the ASP System

The equivalent SDOF parameters of the main structure, together with the corresponding drift demand (θ_d^f) and capacity (θ_t^f) are used as the basis for defining the SDOF system of the aluminum shear panels. The key design parameter is the stiffness ratio between panels and bare frame ($r_p = K^p / K_\mu^f$), which is calibrated to achieve the target drift reduction factor (R_p), as follows [11]:

$$r_p = \frac{p \left(\frac{1}{R_p^2} - 1 \right) \left[1 + a \left(\xi_0^f + \frac{1}{\pi} \cdot \frac{\alpha_y + \mu^c - \alpha_y^\lambda (1 + \mu^c)}{\alpha_y + \mu^c} \cdot R \right) \right]}{\left(1 + a \xi_0^f \right) \cdot \frac{1}{\mu^p} + \frac{2aR}{\pi \mu^p} \left(1 - \frac{1}{\mu^p} \right)} \quad (13)$$

where $p = K_\mu^f / K^f$, μ^c is the cracking ductility of the main structure, and $a = 25$, $\lambda = 0.5$, and $R = 0.6$ are empirical coefficients.

Since the ductility demand (μ^p) of the aluminum panels is not known a priori, an iterative procedure is adopted. In the first step, the panel ductility demand is assumed equal to its ductility capacity, and the process is repeated until convergence is achieved. This procedure allows defining the equivalent SDOF system of the panels and determining their required mechanical properties. In particular, the design stiffness and shear strength of the panels are obtained as: $K^p = r_p K_\mu^f$ and $V^p = K^p \cdot \theta_t \cdot h_{eq} / \mu^p$.

3.4. Vertical Distribution of ASPs

The global stiffness and shear strength obtained for the equivalent SDOF system are distributed along the building height to reconstruct the corresponding MDOF system. This conversion is carried out assuming that: (i) the equivalent viscous damping remains unchanged, and (ii) the yield drift, drift demand, and ductility demand are uniformly distributed over the height. Under these assumptions, the optimal lateral stiffness and strength of the shear panels at the i -th story are obtained as [11]:

$$K_i^p = \frac{V_i}{h_i} \cdot \frac{\sum_{i=1}^N K_{\mu,i}^f h_i^2}{\sum_{i=1}^N V_i h_i} \left(\mu^p + \frac{\mu^f}{\alpha_y} \cdot r_p \right) - \mu^p K_{\mu,i}^f \quad (14)$$

$$V_i^p = K_i^p \cdot \frac{\theta_t \cdot h_i}{\mu^p}$$

where V_i is the design shear force of the ASPs at the i -th story and $K_{\mu,i}^f$ is the corresponding secant stiffness. Finally, the design shear force at each story should be distributed in the plan by defining the number and layout of the panels (Figure 7).

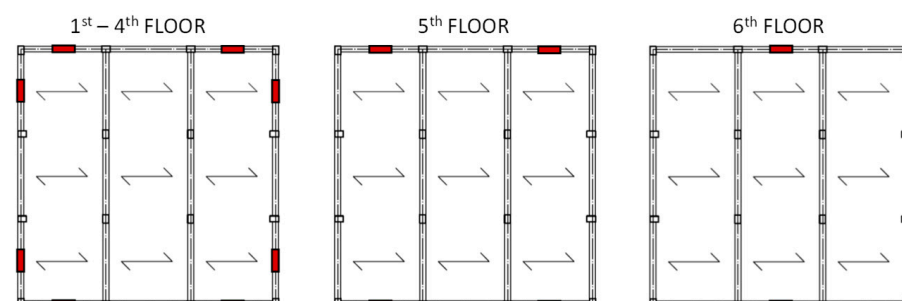


Figure 7. Layout in plan of ASPs.

4. Effectiveness of the Retrofit Strategy

The effectiveness of the proposed retrofit strategy is assessed through nonlinear dynamic analyses performed using seven pairs of natural accelerograms, applied simultaneously in the two horizontal directions. The selected ground motions are taken from

established databases and properly scaled to match the target elastic response spectrum, ensuring spectrum compatibility. The seismic response is evaluated by considering the mean values of the response parameters, in accordance with code-based approaches. The target response spectrum of the Italian Code [12] is used based on the following parameters: soil type C, topographic factor T_1 , and reference life $V_R = 75$ years. A key aspect of the analysis is the modeling of the hysteretic behavior of the ASPs. The features of shear panels made of aluminum alloy EN-AW 1050A tested in [10] are considered in the analysis. Since the panels are properly stiffened to prevent premature buckling, the expected behavior is represented well by a semi-slip model with limited pinching (i.e., pinching 50%) and moderate degradation [4,9]. The seismic performance is primarily evaluated in terms of the inter-story drift ratio (IDR), which provides insight into both global demand and potential damage mechanisms (Figure 8). For the existing buildings, the results highlight very high drift demands, strongly dependent on the ground motion record, with peak IDR values largely exceeding conventional code limits for collapse prevention ($\approx 3\%$). These high demands lead to significant drift concentration, particularly in the intermediate stories, indicating a high likelihood of soft-story mechanisms and potential collapse. In contrast, the retrofitted configurations show a substantial improvement in performance. The introduction of aluminum shear panels leads to a marked reduction in peak IDR values (generally below 1–2%). This indicates that the retrofit strategy effectively mitigates irregularities in deformation demand and prevents the formation of localized failure mechanisms. A further level of verification is carried out by comparing the seismic demand with the chord rotation capacity of structural members, as required by the Italian Code [12]. The chord rotation is directly related to inter-story drift and is evaluated for both uniaxial and biaxial bending conditions, defining a capacity domain for each element. The comparison with time-history demand (Figure 9) shows that demand remains within the capacity limits for all structural members. Overall, the nonlinear dynamic analyses confirm that the retrofit strategy based on aluminum shear panels is highly effective in reducing seismic demand, improving drift control, ensuring a more regular structural response, and preventing collapse mechanisms, thus meeting the required performance objectives.

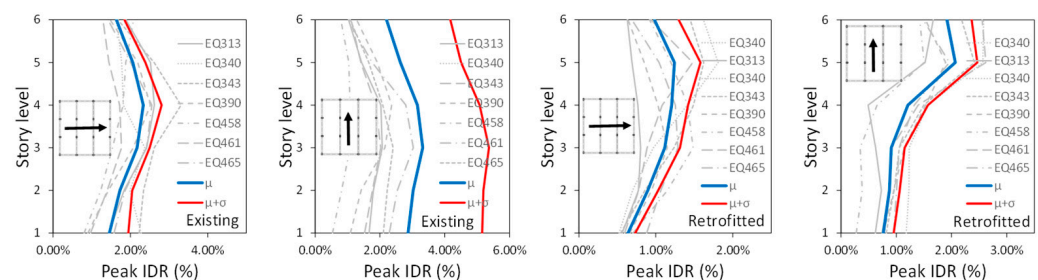


Figure 8. Peak inter-story drift ratio (IDR) distribution along the building height. The arrow indicates the direction in which the IDR is calculated.

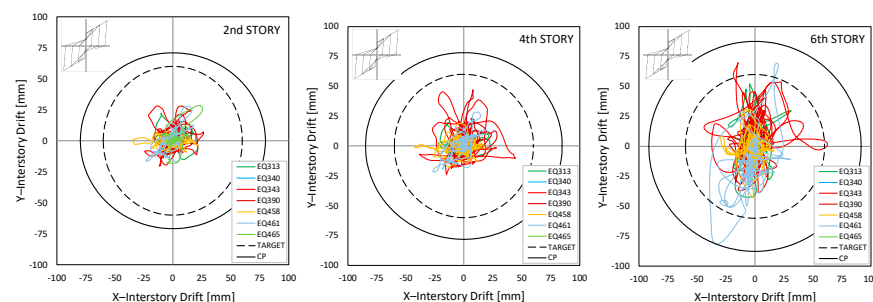


Figure 9. Demand vs. capacity in terms of inter-story drift—CP limit state.

5. Conclusions

The study addresses the lack of practical design methods for aluminum shear panels by proposing a simplified yet effective procedure that accounts for structural nonlinearity and panel–frame interaction, while ensuring an optimal distribution along the building height. Nonlinear dynamic analyses demonstrate that the retrofit strategy is highly effective in reducing inter-story drift demands and eliminating drift concentration. However, several assumptions are introduced, including uniform yield drift, uniform ductility demand, and constant equivalent damping along the building height. These assumptions are considered appropriate for regular low- to mid-rise RC frame structures characterized by a predominantly first-mode response and relatively uniform deformation patterns. Moreover, the proposed retrofit methodology is demonstrated through its application to a single benchmark RC building. Future developments of the methodology will therefore focus on extending the approach to different structural typologies, height configurations, and irregular layouts, to further assess its general applicability and robustness.

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References

1. Trombetti, T.; Dall’Asta, A.; Ragni, L.; Zona, A. Seismic response of structures equipped with metallic yielding devices: State of the art and perspectives. *Eng. Struct.* **2020**, *211*, 110486. [\[CrossRef\]](#)
2. Mazzolani, F.M. *Aluminium Alloy Structures*; E & FN Spon: London, UK, 2001; pp. 1–512.
3. De Matteis, G.; Formisano, A.; Mazzolani, F.M. An innovative methodology for seismic retrofitting of existing RC buildings by metal shear panels. *Earthq. Eng. Struct. Dyn.* **2009**, *38*, 61–78. [\[CrossRef\]](#)
4. Formisano, A.; De Matteis, G.; Mazzolani, F.M. Numerical and experimental behaviour of a full-scale RC structure upgraded with steel and aluminium shear panels. *Comput. Struct.* **2010**, *88*, 1348–1360. [\[CrossRef\]](#)
5. Ferraioli, M.; Lavino, A.; De Matteis, G. A design method for seismic retrofit of reinforced concrete frame buildings using aluminum shear panels. *Arch. Civ. Mech. Eng.* **2023**, *23*, 106. [\[CrossRef\]](#)
6. Ferraioli, M.; Lavino, A.; Mandara, A. Seismic retrofit design method of RC buildings using metallic yielding dampers. *Ing. Sismica* **2020**, *37*, 19–32.
7. Thorburn, L.J.; Kulak, G.L.; Montgomery, C.J. *Analysis of Steel Plate Shear Walls*; Structural Engineering Report No. 107; University of Alberta: Edmonton, AB, Canada, 1983.
8. Sabouri-Ghomi, S.; Ventura, C.E.; Kharrazi, M.H. Shear analysis and design of ductile steel plate walls. *J. Struct. Eng.* **2005**, *131*, 878–889. [\[CrossRef\]](#)
9. De Matteis, G.; D’Agostino, F.; Brando, G. Experimental tests on steel buckling inhibited shear panels. *Open Constr. Build. Technol. J.* **2014**, *8*, 279–288. [\[CrossRef\]](#)
10. Brando, G.; De Matteis, G. Design of low strength-high hardening metal multi-stiffened shear plates. *Eng. Struct.* **2014**, *60*, 2–10. [\[CrossRef\]](#)

11. Kasai, K.; Ito, H. Peak Response Evaluation and Design for Elasto-Plastically Damped Systems. In Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada, 1–6 August 2004.
12. Ministero delle Infrastrutture e dei Trasporti. *NTC 2018: Technical Standards for Constructions*; Official Journal of the Italian Republic: Rome, Italy, 2018.

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