Seismic Retrofitting Concrete Structures with Post-installed Connections in New Zealand

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ABSTRACT

Seismic Retrofitting of concrete structures in New Zealand is of utmost importance, as highlighted by the most recent catastrophic Canterbury earthquakes in 2010 and 2011. With more than 2,800 earthquake-prone buildings in the national earthquake-prone register of New Zealand, ensuring the structural safety of the buildings is urgent and crucial. This paper focuses on the suitability of post-installed anchors and rebars for seismic retrofitting. While effective solutions for post-installed anchor applications through NZS3101 are available, a significant gap exists in the standard's lack of comprehensive coverage for post-installed rebar applications. Drawing from anchoring theories such as EN1992-4, rebar theories such as EN1992-1, and EOTA TR069, and other design theories such as the Critical Shear Crack and EOTA TR066, we examine their applicability to seismic retrofitting and their applicability to New Zealand construction. In this paper, only the European guidelines on the subject are considered as it is considered state-of-art on the subject. In conclusion, this paper advocates for the inclusion of post-installed rebar applications within NZS3101 - aligning with some international practices – and for more guidance on techniques for seismic rehabilitation of existing buildings in the country. By exploring advanced anchoring theories and forthcoming guidance documents, it envisions a future where New Zealand's structures are fortified to withstand seismic forces, ensuring their longevity and safety.

1 INTRODUCTION

The seismic structural design in New Zealand started in 1931 with the publication of the report "Draft General Earthquake Building By-Law" (Cull, 1931). In this report, a uniform lateral force equivalent to an acceleration value of 0.1g times a percentage of the building weight (which fluctuates around 8-10%) was used as seismic demand for the structural design of buildings (Megget, 2006). After 40 years of experience and research, modern seismic design was established in New Zealand with the introduction of Ultimate Limit State (ULS) and Serviceability Limit State (STL), replacing the working stress approach in the New Zealand Standard NZS 4203:1976 and the improved requirements in the New Zealand Standard NZS 3101:1982 in the detailing of plastic hinge regions. Enormous progress has been made in the seismic design of buildings in less than 100 years since the publication of the Draft General Earthquake Building By-Law, providing safer structures with a better understanding of their seismic behaviour. These remarkable upgrades in seismic design requirements highlight the need to evaluate existing buildings designed using older standards to the current New Zealand practice on earthquake engineering. Suppose the evaluation indicates that the seismic performance of the building is worse than required by current official guidelines. In that case, the building should be retrofitted to strengthen its weaknesses and improve its seismic performance.

The technical guidelines "The Seismic Assessments of Existing Buildings" were released in 2017 as part of the modifications in the Building Act to identify earthquake-prone buildings in New Zealand. The primary metric used in the guidelines is the percentage of New Building Standard, %NBS, which is the percentage of Ultimate Limit State shaking that can be resisted by the building while achieving the same minimum level of performance. The seismic capacity of the structural elements is defined by their probable strength, probable drift capacity, and onset of loss of gravity capacity. If the Detailed Seismic Assessment defined in the guidelines applied to an existing building shows an %NBS value of less than 34%, the building must be retrofitted and reassessed.

No official guidelines exist for the seismic retrofit techniques for reinforced concrete (RC) buildings in New Zealand. Currently, practitioner engineers use state-of-the-art experimental research, common engineering practices, and international guidelines for retrofitting RC buildings. An ongoing research group is working on the development of official guidelines for the seismic retrofit of RC buildings following international guidelines such as FEMA 547 (2006) and the Japanese Guidelines for Seismic Retrofit of Existing Reinforced Concrete Buildings (JBDPA, 2001), and potential issues have been identified after discussions with practitioner engineers, academics, and government entities. While abundant experimental research is available with successful seismic performances of retrofitted RC components and buildings, no clear recommendations exist for the connection between the existing and the new components. This paper describes some of the most common retrofitting techniques used to retrofit a building using post-installed anchors and post-installed rebar. The paper also summarizes the design guidelines to be followed in the absence of national standards on the subject.

2 COMMON RETROFITTING TECHNIQUES AND DESIGN OF THEIR POST-INSTALLED CONNECTIONS

2.1 Concrete Jacketing (or Concrete Overlay)

One of the traditional techniques for reinforcing concrete involves augmenting the existing section through the incorporation of a new layer of concrete. The terminology for this application may vary depending on the element and the extent of the strengthening—whether it involves a single surface or multiple surfaces, for instance. In the case of slabs or walls, when an extra layer of concrete is usually applied on the tensile face of the element (refer to Figure 1), the technique is commonly known as "Concrete Overlay." Conversely, when multiple surfaces, such as in beams or columns, undergo this strengthening process, the more prevalent term is "Concrete Jacketing" (refer to Figure 2). The objective in both cases is to achieve a monolithic behaviour between the new and existing sections, ensuring optimal results by considering the flexural and shear capacities of the group.

Figure 1: Concrete overlay application using post-installed mechanical anchor

Figure 2: Concrete jacketing for a column using post-installed rebar [Gkournelos et al 2019]

Eurocode 8 (EN1998-3 - A.4.2) states the use of concrete jacketing/overlay method for increasing the bearing capacity, flexural and/or shear strength, increasing the deformation capacity, or improving the strength of deficient lap-splices of concrete columns and walls. For this, certain simplifying assumptions are taken, such as that the jacketed member behaves monolithically, with full composite action between old and new concrete. Guidance on the preparation of shear interface between the two layers of concrete and the design of post-installed rebar are further explained in sections 2.1 and 2.5 of this paper, respectively.

For the effectiveness of the method, the surface preparations play an important role in this strengthening technique, as described by Fernandes et al (2017). Antoniou (2011) reiterates that and suggests that the shear transfer between concrete layers should be taken by the dowels alone, neglecting the transfer between the interfaces. However, with the advancement of research in the interface shear-friction theories - such as the ones conducted by Vintzileou et al (2018) -, new design methods for calculations of the interface shear were developed and it is possible to calculate the participation of the joint roughness in the shear transfer. Boronsnyoi and Kundu (2022) may be referred to for more details on subject of interface shear-friction.

Accounting for joint roughness could result in a substantial decrease in the number of dowels needed per square meter. To illustrate that, a calculation was conducted using Hilti Profis Engineering software for Seismic Category C2 on a 1.0m x 1.0m x 0.2m generic 25MPa concrete section. This example involved an overlay of 30MPa and 0.12m thickness, exposed to an interface shear of 0.3 N/mm². The outcomes demonstrated that for a smooth joint (with roughness less than 1.5mm), the required quantity of HUS4-H 12x150 would be 24/m² (Figure 3a). In contrast, for a rough joint with roughness greater than or equal to 1.5mm, the quantity would decrease to 15 (Figure 3b), indicating a remarkable 60% reduction. It is important to highlight that this example is illustrative only and shall not be taken as a rule of thumb.

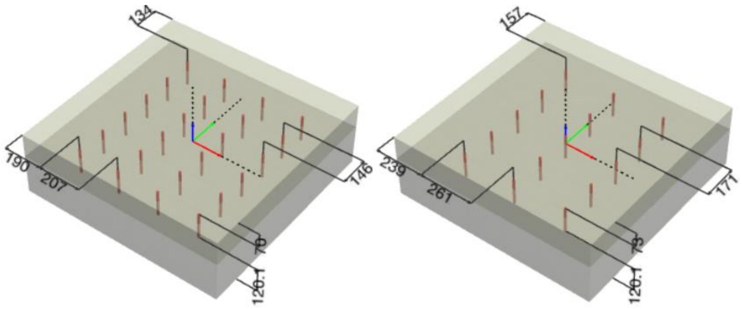

Figure 3: Correlation of the joint roughness and no. of dowels for concrete overlay using Profis Engineering

NZS3101 (Cl 7.7) is often referred to for designs involving shear-friction applications, however, seismic design and post-installed dowels are not covered in the standard. However, clause 7.7.3 allows for "*any other* *shear transfer design methods that result in the prediction of strength in substantial agreement with results of comprehensive tests*", therefore EOTA TR066 appears to be the most updated option for this type of application. It provides a design concept for strengthening existing concrete structures using post-installed anchors. This can be achieved by adding a new concrete layer to existing members or by adding new concrete members that transfer interface shear without significant transverse bending. This design method ensures the monolithic or composite behaviour of different concrete layers by doweling the shear interface and transmitting the tensile forces generated by friction in the shear interface. The three working principles are adhesive bonding and mechanical interlocking, shear friction, and dowel action of reinforcement and/or connectors crossing the interface.

The use of ETA-approved anchors following the methodology stated in the EAD 332347-00-0601 is mandatory for seismic applications, and their resistance and failure mode should be calculated assuming seismic performance category C1 or C2 as per EN1992-4. The interface and connectors (acting in tension) require ten different verifications, including steel and concrete-related failures in both the existing concrete and the concrete overlay.

2.2 Steel Bracing into Existing Concrete Frames

Different from the previously described methodology, the addition of steel bracing into existing concrete frames does not just alter the characteristics of a single element but impacts the load distribution in the entire building. Therefore, it is considered a global seismic retrofit strategy. This approach can enhance the strength, ductility, and stiffness of the building. The braces can be installed either inside or, although less commonly, outside the existing frames and should be placed symmetrically to avoid torsion.

Designed for taking horizontal loads, these braces are typically fixed to the existing structure with post-installed mechanical or chemical anchors in a pinned connection, experiencing only axial loads. It is a standard practice to overlook compression forces in the analysis, assuming that only the tensioned braces resist the loads. However, it is crucial to take precautionary measures to limit buckling (for example by using Buckling Restrained Braces – BRB) and slenderness to prevent failure.

While checking the steel elements is important, it is equally important to design their connection into the concrete frames properly. If not anchored into the structure correctly, the application of the technique would be in vain. According to NZS 3101 Cl 17.5.5, "*post-installed mechanical anchors and post-installed adhesive anchors shall pass the prequalification testing stipulated in ETAG 001, Annex E and be designed in accordance with EOTA TR045*." Currently, EOTA TR 049 is the successor document for ETAG 001 Annex E, and EOTA TR045 has been superseded by EN 1992-4 in early 2020, after the last amendment of NZS3101. This makes TR049 and EN1992-4 the state-of-the-art design method for all anchor designs. While the overall design concept remains the same, EN 1992-4 introduces some important technical changes regarding calculating the resistance of fastenings such as that the critical steel failure and critical concrete-relevant failure modes should be considered separately while calculating the combined resistance check, thereby potentially delivering higher utilization values than ETAG, especially under seismic conditions.

Baseplate rigidity is an important aspect of anchor design. The load distribution in a steel-to-concrete connection is simplified by assuming that the anchor base plate does not deform under the influence of forces. However, no member is fully rigid, and the base plate will deform if loaded enough. To ensure sufficient baseplate rigidity, it is important to check the baseplate deformation under the influence of the applied forces and fasteners used.

2.3 Post-installed Punching Shear Reinforcement for Flat Slabs

Flat slabs are common structural systems in existing reinforced concrete around the globe due to their convenience to design and build, however, they are also characterised by a high risk of punching shear failures and uncertainty under seismic loading, due to the complex stress state in the vicinity of the supports (Ramos et al, 2022).

In existing reinforced concrete buildings around the globe, different techniques are employed to retrofit slabs, including by addition of post-installed shear reinforcement, which, according to Lapi et al (2019), demonstrated to be efficient in increasing the punching strength as it raises the failure criterion and in enhancing ductility.

In this technique, special anchors in combination with an adhesive mortar are used to install punching shear reinforcement, such as Hilti HZA-P - that consists of a reinforcement bar with a diameter of 16mm or 20mm in the upper part, and a smooth shaft with a thread at the end - in inclined holes that are hammer-drilled from the bottom into the concrete slab at a 45° angle. The system is illustrated in Figure 4 below.

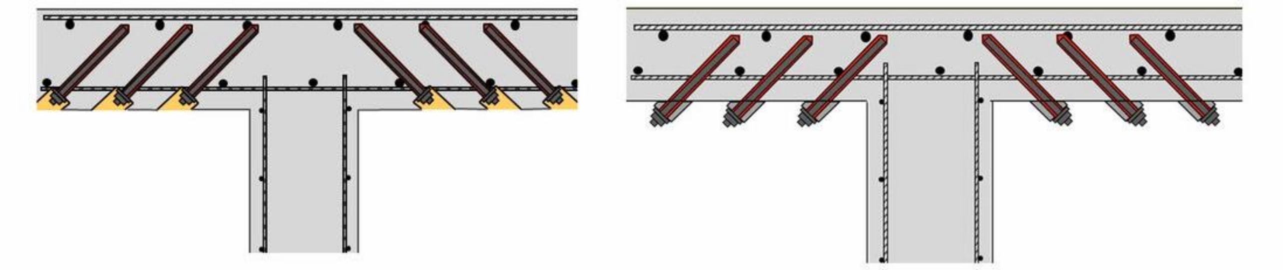

Figure 4: Post-installed punching shear reinforcement applied only from the bottom side of the slab

The strength of the reinforcement bar is crucial in the design, as the smooth shaft and thread are made of steel with higher strength than the reinforcement bar. Once the adhesive mortar has cured, the lower anchor head is installed, which includes an injection washer, a spherical washer, and a nut. To ensure a slip-free anchorage, the annular gaps and the interface between the washer and concrete surface are injected with adhesive mortar through the injection washer. The anchor head is installed in an enlarged part of the drilled hole.

The Critical Shear Crack Theory is a reliable method for designing one and two-way slabs that fail in shear and punching shear, respectively. Developed in Switzerland in the 1980s, it is currently the theoretical basis of the Swiss Code for Concrete Structures with reference to members without shear reinforcement. The theory uses a physical model to calculate the strength and deformation capacity of members failing in shear or punching shear. It also considers the opening and roughness of a critical shear crack that leads to failure, as described by Muttoni and Ruiz (2007).

An extension of this theory was performed at the Swiss Federal Institute of Technology of Lausanne (Switzerland) in cooperation with the scientific consultants of Hilti to account for the influence of the many mechanical and geometric parameters of the slabs and shear reinforcement. This effort resulted in a rather simple and clear design concept that is widely used in design codes, such as the Fib Model Code 2010 or the Swiss Code for Concrete Structures SIA 262 (2003).

One effective and cost-efficient technique that can be used to strengthen structures without modifying their size is the post-installed punching shear reinforcement design method. This method is particularly useful for refurbishing and strengthening old structures, such as parking decks, where traffic space is critical. The embedded anchorage can be covered with fire protection mortar, making it aesthetically pleasing and invisible after installation.

2.4 New Concrete Elements

2.4.1 Addition of Shear Walls

The method consists of the incorporation of new shear walls at picked locations in the building perimeter - either within the existing frames or external to them (Figure 5) – or in internal locations. It is desired that these locations maintain symmetry with the building to avoid torsion. This technique shares advantages with seismic retrofit with steel braces (i.e. strength, stiffness, and ductility). Notably, it offers the additional benefit of drawing more loads from the concrete frames due to the substantial dimensions and high stiffness of the shear walls. Therefore, with the reduction of the demands applied to other structural elements, it might not be required to strengthen other columns and beams in the building (Antoniou, 2022).

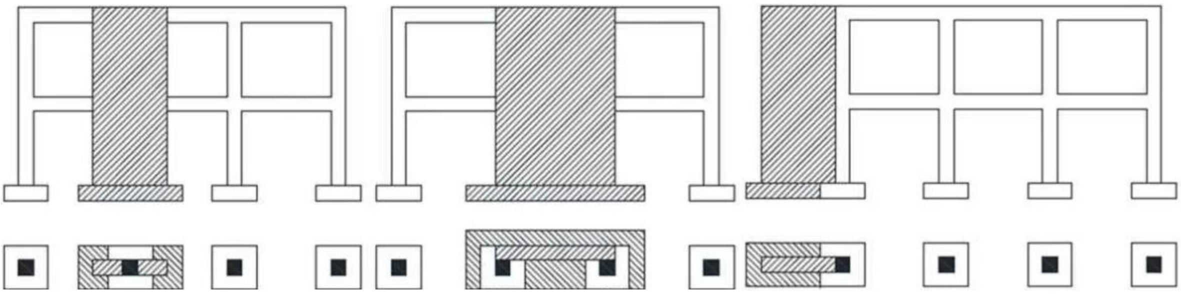

Figure 5: View and cross-section above the foundation of RC frames strengthened with new RC walls placed internally, externally, or as buttress [Tsionis et al. 2014]

These new shear walls are usually designed to achieve yielding failure in flexure before the shear, and the plastic hinges and yielding are only expected to occur at the base.

The incorporated elements should be anchored into the existing structures to ensure the expected load path and desired behaviour. For this, post-installed rebars shall be used, as they will be able to act as dowels as well as lap splices between the new and existing concrete elements.

Boronsnyoi and Genesio (2021) comment that NZS3101, Eurocode 2 (EN 1992-1-1), and Eurocode 8 (EN 1998-1) do not provide guidelines for designing anchorages and lap splices with post-installed rebars. Currently, the only guideline that addresses this topic is the fib Model Code 2010, which suggests that using post-installed rebars for rebar connections is permissible for all applications where straight cast-in-place rebars are allowed. For this, it requires that the suitability of post-installed rebars be proven through an independent approval process and cites the EOTA TR023 (superseded by the EAD 330087-01).

The basic anchorage length formulae in EN 1992-1-1 and fib Model Code 2010 have a similar structure, demonstrated in Equation 1, which defines the minimum anchorage length required for the steel to yield before pullout or other concrete-related failure mode occurs:

$$l_{b,rqd} = \left(\frac{d_b}{4}\right)\left(\frac{f_{yd}}{f_{bd}}\right) \quad (1)$$

where $l_{b,rqd}$ = basic anchorage length; d_b= rebar diameter; f_{yd} = yield strength of the rebar; and f_{bd}= bond strength of the epoxy.

2.4.2 Slab Strengthening with Addition of Beams

One of the common retrofitting techniques for existing slabs is to add structural members made of steel or concrete to divide the slab into smaller sections, enhancing its stiffness and resulting in a reduction of the slab span, reducing internal stresses and deformation of the slab.

To ensure effective load transfer to the new beam, it is necessary to anchor the new stirrups to the existing slab using an approved epoxy mortar (Figure 6) and the longitudinal reinforcement into existing beams, columns or walls supporting the slab (Figure 7). Additionally, proper roughening of the interface is essential to guarantee adhesion and facilitate the appropriate transfer of shear stresses between both elements. This meticulous approach ensures the reinforced structure functions cohesively, maximizing the benefits of increased stiffness and minimized internal stresses in the strengthened slab.

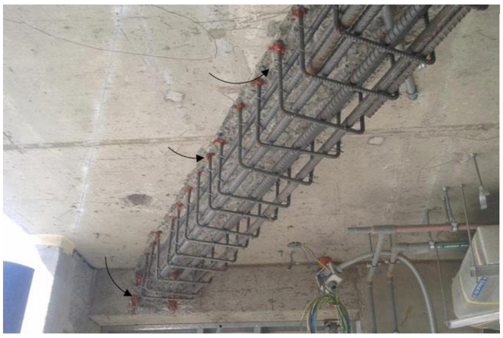

Figure 6: Slab strengthening by adding concrete beam [Abdelrahman 2023]

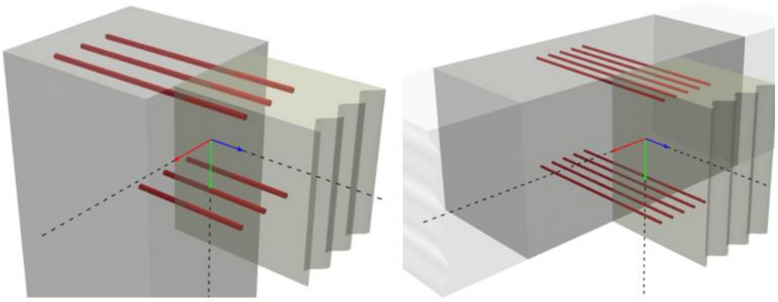

Figure 7: 3D representation of beam-to-column and beam-to-beam connections on Hilti Profis Engineering.

EOTA TR 069 is a technical report that provides a design method used to calculate the development length of post-installed rebars in moment-resisting connections designed for static, quasi-static or seismic loading. The method unifies the rebar theory for cast-in rebars and the anchor theory for cast-in or post-installed anchor singular connections and applies to single or group rebars with the same type, size, and length. For seismic actions, Eurocode 8 (EN 1998-1) and its National Annexes are required. The method is based on a hierarchy of strengths between steel yielding, concrete cone breakout, and bond-splitting resistance.

The concrete can be cracked or non-cracked in the region of the post-installed rebar connection. EOTA TR 069 emphasizes that the condition of the concrete for the service life of the structural connection shall be determined by the designer. Cracked concrete is always assumed unless uncracked concrete conditions can be guaranteed (e.g., EN 1992-4, Eq. (4.4)). Under seismic action, the crack width can be significantly larger compared to static loading and is influenced by several factors such as type of connections, design assumptions (i.e., elastic vs. ductile design), the deformability of the existing member, capacity design considerations, the ratio between embedment length and height of the existing member, etc. If no detailed information is available, EOTA TR 069 recommends values for the maximum design crack widths, based on the Ductility Classes, up to w = 0.8 mm. The decisive design seismic resistance for the post-installed rebar according to EOTA TR069 is described in Equation 2 below.

$$R_{d,eq} = min\left(N_{Rd,y,eq}; N_{Rd,c,eq}; N_{Rd,sp,eq}\right) \quad (2)$$

where $R_{d,eq}$ = design seismic resistance; $N_{Rd,y,eq}$ = steel yielding resistance in seismic; $N_{Rd,c,eq}$ = concrete breakout; and $N_{Rd,sp,eq}$ = bond-splitting resistance in seismic.

3 CONCLUSIONS

As per the national earthquake-prone register of New Zealand, several buildings need to be retrofitted to ensure safety of the building and its occupants. However, there are no comprehensive guidelines on the subject in New Zealand. Many common retrofitting techniques such as concrete jacketing, concrete overlay, steel bracing, etc. discussed in this paper make use of post-installed anchor and/or post-installed rebar. While New Zealand Concrete Structures standard NZS 3101 includes guidance on the design of post-installed anchors, it does not address the design of applications using post-installed rebars. In the absence of national standards, guidance may be taken from numerous European Assessment Documents (EAD) and Technical

Reports (TR) recently published by the European Organization for Technical Assessment (EOTA) on the subject. However, in the long term, bringing a comprehensive guideline on retrofitting of concrete structures would greatly benefit the New Zealand construction industry. At the least, design guidance on post-installed rebar should be included in NZS 3101. In addition, adoption of new design methods for calculations of the interface shear based on the advancement of research should be explored.

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