Advanced seismic design of concrete-to-concrete structural connections

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ABSTRACT

The European Organization for Technical Assessment (EOTA) recently published Technical Report TR 066 (2020) for seismic design of concrete overlays and TR 069 (2021) for seismic design of post-installed rebar (PIR) connections with improved bond-splitting behaviour. These documents represent the current state-of-the-art in the seismic design of concrete-to-concrete structural connections. This paper provides an overview of TR 066 and TR 069 together with a short literature review of their development and recommends future actions for their adoption in New Zealand.

1 INTRODUCTION

Post-installed concrete-to-concrete connections are common applications in construction. As one of the examples, it can be used in the seismic strengthening of concrete buildings and bridges, as this may require the addition of new concrete members or overlays. One way of connecting new concrete to existing concrete is using post-installed rebar (PIR) connections. International practice in the design of PIR connections is based on classic reinforced concrete theory that assumes equivalent bond performance of PIR to that of cast-in rebars. For example, in Australia, AS 5216:2021 allows PIR connection design using the provisions of AS 3600:2018 for those injection mortar systems that have been assessed as per the European Assessment Document EAD 330087 and hold a European Technical Assessment (ETA) as proof of equivalence. There is experimental evidence that the bond performance of PIR can be better than that of cast-in rebars, however, this potential was not utilized until recently, due to the lack of standards.

1.1 Status quo in New Zealand Standard NZS 3101

New Zealand Concrete structures standard NZS 3101 does not currently address post-installed concrete-to-concrete structural connections. The standard is structured in a way that it gives additional design requirements for structures designed for earthquake effects in each application, when relevant. Therefore, it is easy to identify the requirements for members designed for e.g. ductility in earthquakes. In the topics covered by this paper, two sections are directly relevant in the current version of NZS 3101 (2006); Clause 7.7 *Shear friction* and Chapter 8 *Stress development, detailing and splicing of reinforcement and tendons*.

NZS 3101 was first published in 1982 and as a basis – with the exception of the provisions for seismic loading –, ACI 318-77 has been used with minor modification. After its first revision, NZS 3101 was re-issued in 1995 and minor changes have been made to facilitate a planned future harmonization with the Australian Concrete Structures Code. Non-seismic parts of NZS 3101 were still based largely on ACI, with some of the new provisions of ACI 318-89 being incorporated into NZS 3101 (1995). After a second revision, NZS 3101 was re-issued in 2006 and is in force at the date of submitting this paper for publication. During the second revision, various technical advancements and improvements have been incorporated that have been developed since 1995. Non-seismic parts of NZS 3101 (2006) are largely based on ACI 318-02.

When considering the shear transfer across a plane (i.e. an interface between two concretes cast at different times (e.g. a cold joint) - an interface between dissimilar materials, or an existing or potential crack, or where there is an abrupt change in section, (i.e. the junction between a corbel and other structural members), NZS 3101 Clause 7.7 suggests a classic shear-friction design method since the first edition of NZS 3101 published in 1982. The model is based on research conducted by Birkeland and Birkeland (1966) and Mattock and Hawkins (1972). Commentary Clause C7.7.3 of NZS 3101 adds that other relationships that give a closer estimate of shear-transfer strength may be used too, and refers to Mattock (1974, 1975) and the PCI Handbook (1992). In the NZS 3101 shear-friction model, a crack is assumed to occur along the shear plane considered, and adequately anchored shear-friction reinforcement is assumed to be suitably distributed across the crack to develop the yield strength on both sides of the crack; the shear-friction reinforcement anchorage must engage primary reinforcement. It is noted that NZS 3101 does not provide additional design requirements for the shear-friction design of structures for earthquake effects.

The current formulae for development length or lap splice length in tension and compression (Chapter 8 in NZS 3101) have been added to the standard in 1995. Commentary Clause C8 of NZS 3101 reveals that the *development length formulae for tension* are based on research conducted before the 1980's, namely the research of Orangun, Jirsa, and Breen (1975, 1977), as the basis of the ACI 318 development and splice length in tension, in combination with the research of Jirsa, Lutz and Gergely (1979). The parameters accounting for the beneficial effects of transverse reinforcement were checked in the original research based on the experiments of Untrauer and Warren (1977). The NZS 3101 provisions on *development length in compression* are similar to the provisions given in ACI 318-89. It is noted that the minimum lengths specified for column splices contained originally in the 1956 ACI Building Code and have been carried forward in the later code editions and extended to compression bars in beams and to higher strength steels later. No changes, however, have been made in the provisions for compression splices since the 1971 ACI code edition. The NZS 3101 provisions on *lap splice lengths* follow the recommendations of ACI Committee 408 – also adopted by ACI 318 – i.e. splice lengths and development lengths for deformed bars and wires are the same. For *non-contact splices*, NZS 3101 adopted the concept of the effective lap splice length proposed first by Robinson et al (1974) and later studied by Sagan et al (1988, 1991). NZS 3101 provides additional design requirements for the design of development lengths or lap splice lengths for earthquake effects.

2 RESEARCH ON SHEAR-FRICTION MODELS

Shear-friction research has been originated in the 1960s and the basic assumption in the original idea was that force transfer at a concrete-to-concrete interface subjected to concurrent shear and compression is utilized by friction only. Since shear reinforcement usually crosses the interface and normal stresses can also be present to the shear plane, some further parameters have been added later to the originally proposed models (Santos and Júlio 2012, 2014; Palieraki et al 2021, 2022a, 2022b). The main contribution to the overall shear resistance is resulted from three mechanisms: 1) adhesive bonding and mechanical interlocking; 2) shear friction due to external compression forces perpendicular to the interface and clamping forces due to reinforcement and/or connectors; 3) dowel action of reinforcement and/or connectors crossing the interface. Paulay, Park and Phillips (1974) were the first to formulate how these mechanisms function; in their paper a distinction is made between bending, shearing and kinking in the dowel action mechanism of reinforcement or steel shear connectors. The *fib* Model Code 2010 was the first design code that included the full model for concrete-to-concrete load transfer across interfaces, including all the three mechanisms introduced above. Randl (2013) provided detailed background information on this subject.

2.1 The EOTA TR 066 approach

For the interface shear-friction capacity, EOTA TR 066 (similarly to the *fib* Model Code 2010) applies the linear superposition of the three mechanisms introduced above, limited by the capacity of the diagonal concrete strut that is expressed as a function of the concrete compressive strength. A minimum reinforcement ratio of $\rho_{min} = 0.1\%$ for beams and $\rho_{min} = 0.05\%$ for slabs is suggested in EOTA TR 066. For the derivation of the acting seismic forces, EOTA TR 066 suggests that the most adverse combination shall be used for the design of the interface, based on the combinations of actions required by the local seismic code in use. There are ten different required verifications for the interface and the connectors (acting in tension), including steel and concrete related failures in both the existing concrete and in the concrete overlay added (Fig. 1). The resistance of the connectors and the decisive failure mode shall be calculated assuming seismic performance category C1 or C2 depending on the application and the design assumption. Guidance in this regard is provided in EN 1992-4 (Note: EN 1992-4 is cited in Clause 17.5.5 of NZS 3101 being the superseding document for EOTA TR 045). Depending on the type of application, the impact of the decisive failure modes of the connectors (e.g., concrete cone, pull-out, combined pull-out and concrete cone, splitting, blow-out, or steel yielding) on the desired behaviour of the interface shall be considered by the designer. Steel yielding of the connectors might be required as decisive failure mode to ensure a ductile behaviour of primary structural members (e.g. connection of shear walls to an existing frame). Concrete related failure modes might be acceptable in interfaces between members that are not supposed to undergo significant deformation during the seismic event and/or where a high redundancy is provided, and the failure of single connector is not expected to endanger the integrity of the structure (e.g. floor thickening).

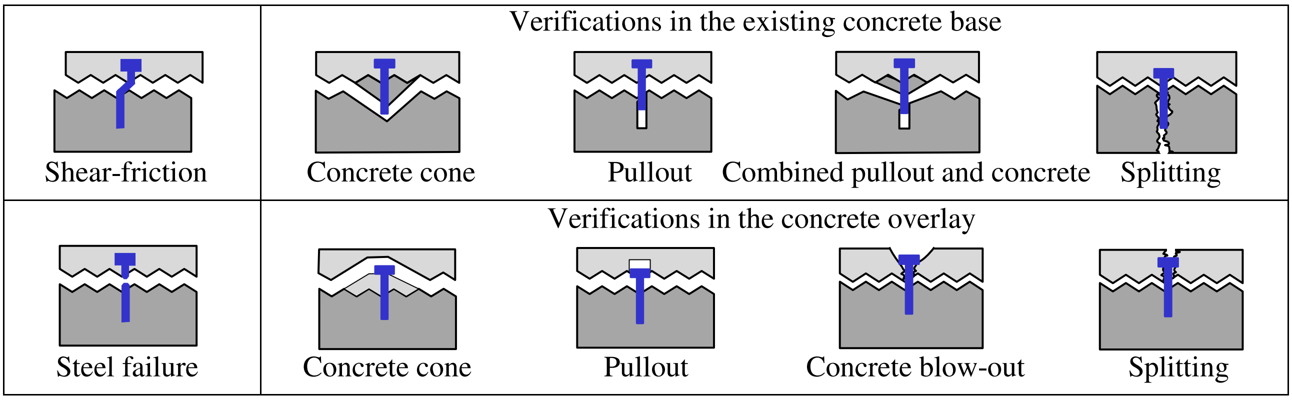

Figure 1: Required verifications for the interface and the connectors in EOTA TR 066

2.2 Adoption of EOTA TR 066 in New Zealand

The shear-friction model proposed in NZS 3101 is technically the Birkeland and Birkeland (1966) formula with certain restrictions, and as such, one of the most conservative shear-friction models published during the last six decades. Readers can find detailed comparisons of shear-friction models in the papers of Santos and

Júlio (2012, 2014). By its original purpose, the shear-friction model of Birkeland and Birkeland (1966) was not developed for the use under cyclic seismic loading that results in a major challenge for the current NZS 3101 shear-friction design method. Current research has revealed that the contribution of the three mechanisms introduced in the *fib* Model Code 2010 model for concrete-to-concrete load transfer across interfaces is different for static loading and for cyclic loading (Palieraki et al 2022a, 2022b), and these differences have been incorporated into the EOTA TR 066 seismic design method.

The EOTA TR 066 design method is a straightforward approach and can provide great help to New Zealand practitioners in the seismic design of concrete-to-concrete interfaces with post-installed shear connectors, which hold a European Technical Assessment (ETA) in accordance with EAD 332347. Such design can be easily adopted by New Zealand professionals since majority of the required verifications introduced in EOTA TR 066 are in accordance with Clause 17.5.5 of NZS 3101. It is noted that EOTA TR 066 cannot be directly applied for the seismic design of concrete-to-concrete interfaces with post-installed hooked reinforcing bars (since conventional reinforcing bars do not have ETA for the use in concrete overlays). The contribution factor model proposed by Palieraki et al (2022a, 2022b) based on the research conducted at the National Technical University of Athens (NTUA), has a great potential for further development and can be a good candidate for future adoption in NZS 3101 for those concrete overlay applications, which utilize post-installed hooked conventional reinforcing bars. However, more research is needed in this field.

3 RESEARCH ON MOMENT RESISTING CONNECTIONS

Until recently, post-installed rebar connection design was based on the EAD 330087 assessment process of injection mortar systems that verified the equivalency of the load-displacement behaviour between cast-in rebars and post-installed rebars. As a consequence, the range of applications for post-installed rebar connections was rather limited (mostly to splice overlap for slabs and beams, or end anchoring for simply supported slabs and beams, or connections for primarily in compression). Post-installed rebar connections with EAD 330087 assessed injection mortar systems can only be executed with straight rebars for those applications that are permitted for cast-in rebars in Eurocode 2 (EN 1992-1-1) for Europe, in AS 3600 for Australia (based on AS 5216), or in NZS 3101 for New Zealand (based on Engineering Judgement). Therefore, moment resisting connections must also be executed with splices (i.e. creating planned overlaps of post-installed rebars to cast-in rebars). This, however, is not feasible in many cases when such connections were not planned originally. The load-bearing capacity of such lapped joints is limited to the load-bearing capacity of the weaker element; typically the cast-in rebar. The potential in the high bond capacity of the injection mortar systems cannot be fully exploited since EAD 330087 caps the bond strength of the injection mortar systems to that of cast-in rebars.

EOTA TR 069 allows the design of moment resisting connections with post-installed rebars under static, quasi-static and seismic loading conditions without the need of an overlap splice configuration. The injection mortar systems shall be assessed by EAD 332402. The moment resisting connections covered by EOTA TR 069 can be categorised to two main types depending on the primary action acting on the newly attached element: 1) members subjected to compression and to a limited amount of bending (column-to-foundation/slab joints, CFJ; wall-to-foundation/slab joints, WFJ) or 2) members subjected mainly to bending (slab-to-wall joints, SWJ; beam-to-wall joints, BWJ; beam-to-column joints, BCJ). The main difference between these two types of connections is in their reinforcement ratios (Cattaneo et al, 2021).

For the first group of members (CFJ and WFJ), in an early study Tanaka and Oba (2001) conducted cyclic loading tests on column-to-foundation joints (CFJ) and found for post-installed rebar connections (when concrete cone failure was avoided) an equivalent behaviour to cast-in rebar connections with bent hooks. Later Mahrenholtz (2012) and Herzog (2015) and most recently Mahadik et al (2018, 2021) performed FE simulations and comparative laboratory experiments on column-to-foundation joints (CFJ) and confirmed equivalent behaviour between post-installed rebar connections and cast-in rebar connections with bent hooks. Suwa et al (2016) studied wall-to-foundation joints (WFJ) and confirmed an acceptable seismic performance using post-installed rebar connections, provided steel yielding is ensured as the dominant failure mode.

For the second group of members (SWJ, BWJ and BCJ), the earliest studies by Kupfer et al (2003) and Hamad et al (2006) on full scale RC frame node models with either cast-in rebars or post-installed rebars demonstrated an equivalent behaviour for BCJ under static loading. Recently, Mahadik et al (2020) confirmed an equivalent behaviour for BCJ under cyclic loading between post-installed rebar connections and cast-in rebar connections.

It is noted for the readers' interest that the development of the framework for the unified design approach proposed in EOTA TR 069 is summarized in the PhD thesis of Mahadik (2022).

3.1 The EOTA TR 069 approach

EOTA TR 069 is based on a simplified failure hierarchy for post-installed rebar connections that can be considered as an attempted unification of the classic "rebar theory" in reinforced concrete structural design for cast-in rebars and the classic "anchor theory" for cast-in or post-installed anchor singular connections (this latter is also called as Concrete Capacity Design, after Fuchs et al, 1995). This unified design approach to calculate the development length (that is called anchorage length in the Eurocodes) of post-installed rebars in moment resisting connections in accordance with EOTA TR 069 is based on the establishment of a hierarchy of strengths between the following resistances (Fig. 2):

- Steel yielding
- Concrete cone breakout
- Bond-splitting resistance

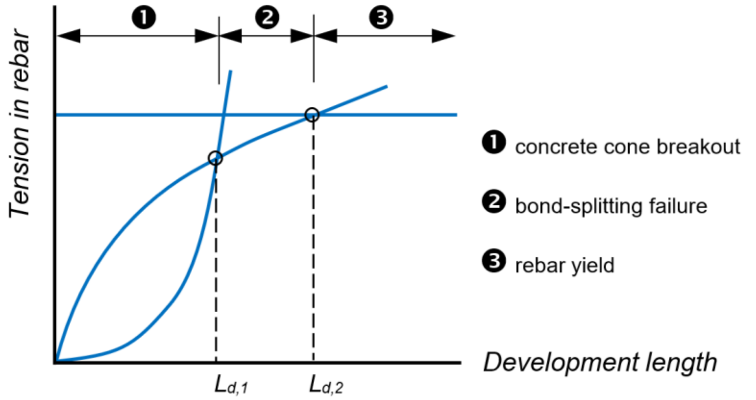

Figure 2: EOTA TR 069 hierarchy of strengths

The EOTA TR 069 design method is valid for single rebars and group of rebars. If rebars are installed in a group, only rebars with the same type, size, and length can be used. EOTA TR 069 specifies that under seismic actions the requirements of Eurocode 8 (EN 1998-1) and its National Annexes apply. The Ductility Classes in Eurocode 8 (EN 1998-1) DCL, DCM and DCH refer to structural behaviour with low, medium and high capacity to dissipate energy, respectively. It is noted that the Ductility Classes DCL/DCM/DCH are not identical to the ductility classes defined in NZS 3101. The concrete can be cracked or non-cracked in the region of the post-installed rebar connection and 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), deformability of the existing member, capacity design considerations, ratio between embedment length and height of the existing member, etc. If no detailed information is available, e.g. results of finite element modelling, EOTA TR 069 recommends values for the maximum design crack widths, based on the Ductility Classes, up to w = 0.8 mm. The embedment length calculated by EOTA TR 069 is not allowed to be shorter than the minimum required anchorage length in accordance with Eurocode 2 (EN 1992-1-1) and the applicable National Annexes. The design seismic resistance ($R_{d,eq}$), expressed as the total tension force in the post-installed rebar used for moment resisting connections, is calculated for each failure mode based on characteristic resistances and corresponding partial safety factors. The decisive design seismic resistance for the post-installed rebar is calculated as $R_{d,eq} = N_{Rd,y,eq} \leq \min(N_{Rd,c,eq}; N_{Rd,sp,eq})$, where $N_{Rd,y,eq}$ = seismic design resistance to yielding of the post-installed rebars; $N_{Rd,c,eq}$ = seismic design concrete cone break-out resistance of the post-installed rebars (based on EN 1992-4); $N_{Rd,sp,eq}$ = seismic design bond-splitting resistance of the post-installed rebars (based on an extended version of the *fib* Model Code 2010 bond-splitting model).

3.2 Adoption of EOTA TR 069 in New Zealand

In contrast to EOTA TR 066, the New Zealand adoption of EOTA TR 069 is less simple. Currently, NZS 3101 does not cover the design of post-installed rebar connections and no other New Zealand standard covers the topic either. The logical solution would be to include the design of post-installed rebar connections in NZS 3101, in the same way as the new generation concrete design codes include it (e.g. *fib* Model Code 2010 and Draft *fib* Model Code 2020). The schedule of the next revision of NZS 3101 is, however, not known at the date of submitting this paper for publication. In interim, similarly to the Australian code pathway example, an alternative can be proposed to accelerate the acceptance and use of state-of-the-art international knowledge in New Zealand and encourage the regulator to embrace such best practices in the New Zealand standards network. In Australia, AEFAC (Australian Engineered Fasteners and Anchors Council) published its Technical Note TN-08 in 2019 that allows the use of AS 3600 for the design of post-installed rebars with injection mortar systems assessed by EAD 330087. The AEFAC Technical Note TN-08 later became the basis of the technical discussions in the Standards Australia ME-029 (Fasteners) Technical Committee meetings, and as a result, its content has been incorporated into AS 5216:2021. A similar approach can be suggested in New Zealand too. Professional associations like Concrete NZ and SESOC have history in publishing peer-reviewed technical guidelines and best practice documents, and they are potential candidates for creating a similar, New Zealand relevant document to the AEFAC Technical Note TN-08. The New Zealand construction industry would greatly benefit from such efforts since practicing engineers currently have to rely on the EOTA publications and their 'weak link' to Eurocodes when post-installed rebar connections are designed in seismic rehabilitation projects involving concrete-to-concrete connections. This issue opens challenges not only for the structural engineering community with the need of familiarize with the European product qualification and design standards to adopt those methods within the New Zealand standards' design, but also the Building Consent Authorities (BCA) in approving such Alternative Solutions during the building consent approval processes. Since all the related EOTA documents are available and several injection mortar systems are easily accessible in the New Zealand market with ETA approvals, it would be relatively easy and straightforward to provide a full recommendation package that covers static loads, seismic loads and fire design of concrete-to-concrete connections. Such local document could support the safe and economical use of post-installed rebar systems in the local structural engineering community without any demand of extra education around e.g. the Eurocodes.

4 CONCLUSIONS

New Zealand Concrete structures standard NZS 3101 currently does not address post-installed concrete-to-concrete structural connections, on the contrary to the recent international trends in the new generation concrete design codes (e.g. *fib* Model Code 2010 and Draft *fib* Model Code 2020) which include this topic directly. Another example is AS 5216 that delegates the design of post-installed rebars to AS 3600. The European Organization for Technical Assessment (EOTA) recently published numerous European Assessment Documents (EAD) and Technical Reports (TR) that provide guidelines for the product assessment of injection mortar systems and design recommendations for post-installed concrete-to-concrete structural connections. This paper summarized the context of EOTA TR 066 and EOTA TR 069. The New Zealand construction industry would greatly benefit from the local adoption of these international state-of-the-art documents. Adoption of EOTA TR 066 seems to be relatively simple since its content is in alignment with the NZS 3101 provisions and could be added to it as Amendment. Adoption of EOTA TR 069 is more challenging due to the lack of flexible local codes and regulations framework and it, therefore, calls the relevant New Zealand professional associations into action.

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