DESIGN RECOMMENDATIONS FOR SEATING ANGLE RETROFITS

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ABSTRACT

Existing precast hollow-core floors commonly have insufficient seating lengths, which makes them prone to Loss of Support failure when subjected to earthquake-imposed demands. A supplementary seating retrofit, such as a seating angle, can be used to prevent collapse when the floor unseats. The absence of design guidance for such seating retrofits has resulted in a wide range of different design and detailing approaches that often underestimate the demands on the post-installed anchors and seating angles. This paper addresses the lack of design guidance by introducing two design methodologies for seating angle retrofits. The first design approach entails design steps for seating angles installed hard up against the soffit of the floor. Capacity-design philosophy is used to ensure the post-installed anchors can withstand the force demands arising from earthquake-imposed deformations. The second recommended approach omits these high demands on the post-installed anchors by leaving a gap between the seating angle and the floor soffit and partially filling this gap with a deformable infill strip. Using these two proposed design recommendations ensures that the seating angle and post-installed anchors can safely support the precast flooring unit if it unseats.

1 BACKGROUND

Precast hollow-core floors are widespread in New Zealand's multi-storey building stock. Advantages such as low cost, lightweight, span capability and ease of construction made the hollow-core floor a popular flooring system, particularly during the construction boom in the 1980s. Until the early 2000s, there were no stringent provisions that outlined how to detail the support for the hollow-core floors. Consequently, the support conditions and seating lengths of hollow-core floors varied significantly, primarily depending on regional practice and contractors' preferences. A nominal seating length of 50 mm was typically specified, following 1970s North American practice, but a review of original drawings of hollow-core floor buildings in Wellington indicated that seating lengths as short as 30 mm were specified in a substantial number of cases (Puranam et al. 2021). In addition, the influence of tolerances during installation could cause the actual seating to be even shorter (MBIE et al. 2018; PCFOG 2009).

The super-assembly test conducted by Matthews (2003) exposed crucial shortcomings of the typical hollow-core floor connection detailing that was used since the 1980s. In response, the third amendment to the concrete structures standard NZS3101:1995 was published in 2004 (SNZ 2004a), making a seating length of at least 75 mm and the use of low-friction bearing strips mandatory. More recent updates to NZS3101 have further increased the required seating length depending on the configuration of a building.

Based on the findings from the Matthews experiment (2003) and subsequent testing on existing hollow-core floor details (Corney et al. 2018; Jensen 2006; Liew 2004; Woods 2008), procedures to assess the seismic capacity of hollow-core floors were developed. These assessment procedures were first published by Fenwick et al. (2010) and then adopted and refined for the technical proposal to revise Section C5 (Concrete Buildings) of the "Guidelines for Detailed Seismic Assessment of Buildings" (MBIE et al. 2018), subsequently referred to as assessment guidelines C5. Three primary failure modes were identified in these assessment procedures, namely Loss of Support (LOS), Negative Moment Failure (NMF) and Positive Moment Failure (PMF).

Seismic assessment of pre-2000s hollow-core floor buildings (using the assessment guidelines C5 (MBIE et al. 2018)) will often find LOS to be the controlling failure mode, though this depends on the provided seating length and other building characteristics (Puranam et al. 2021).

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The factors taken into account when assessing for LOS are:

(a) Movements due to relative rotation of the supporting member/beam,

(b) Elongation of the adjacent beam or unit movement due to plastic strain in the starter bars,

(c) Spalling at the seating beam ledge and at the back face of the hollow-core unit,

(d) Creep, shrinkage and temperature-related deformations,

(e) Construction tolerances, and

(f) Required bearing length.

While the assessment procedures for hollow-core floors have been well established, only limited guidance was provided on retrofit techniques. In practice, a steel angle or hollow section affixed to the support member is the most-widespread solution to extend the short original seating and prevent collapse by LOS. However, the lack of design and detailing guidance for such angle retrofits resulted in a number of different seating angle configurations that have been installed in existing buildings. Several concerns have been raised on the adequacy of the design and detailing features of these typical seating angle configurations.

A floor-to-beam connection with a typical seating angle configuration is depicted in Figure 1. This connection is shown as undergoing an earthquake-induced negative support rotation and pull-off displacement due to the elongation of the adjacent beam. The relative rotation causes the floor to pry over the seating angle, generating a vertical reaction and an associated horizontal friction force at the top leg of the angle. The forces are transferred through the angle and resisted in shear and tension by the post-installed anchors and a compression reaction at the vertical leg.

The main concern associated with the design and detailing of this typical seating angle configuration is that it is not practical to accurately estimate the deformation-induced force on the post-installed anchors, which may lead to sudden brittle failure if the anchors are overloaded. The reasons it is not practical to accurately estimate the force demand are:

- As indicated in Figure 1, the imposed force demands on the anchors may be greater than just the gravity shear, $V_{Gravity}$. The shear force in the anchors, V_{Anchor}, is the sum of the gravity shear, $V_{Gravity}$, and the interface shear, $V_{Interface}$. While the gravity shear force is known, the interface shear force is highly variable. The interface shear consists of (1) the shear resistance from the starter bars acting in dowel action, (2) the shear resistance by the in-situ concrete plugs protruding from the beam into the cells and (3) the shear friction associated with a compression reaction at the back face of the floor. Because of the variability of the involved interface shear components combined with the high uncertainty of the as-built connection conditions, the interface shear resistance cannot reliably be quantified.
- There is uncertainty about at what distance x_1 along the horizontal leg this shear reaction will be transferred into the angle. Without knowing the location of the shear force, the tension force in the anchor, T_{Anchor}, cannot be determined.
- Similarly, the location of the compression reaction C_C, between the seating angle and the support beam is unknown. When the compression reaction, C_C, increases, angle deformations may cause the compression force to shift up towards the anchors. The smaller the lever arm between the compression

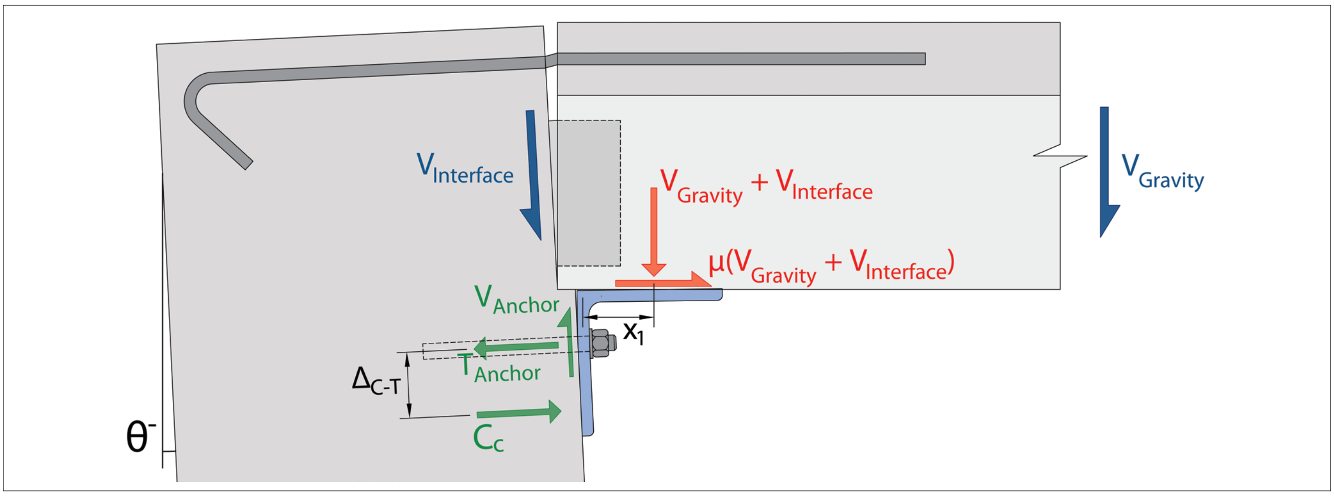

Figure 1: Hollow-core floor to beam connection with a typical existing seating angle under negative rotation

reaction and the post-installed anchors, $\Delta_{C\text{-}T}$, the larger the tension force in the anchors. This effect can result in anchor failure.

Additionally, until recently, guidance has not been provided on which load combinations appropriately represent the gravity load demands on the angle during and after the earthquake.

Furthermore, improper seating angle design and detailing may not only lead to retrofit failure but can also adversely affect the floor performance, i.e. triggering unexpected floor failure modes. Parr et al. (2019) demonstrated that NMF could be triggered when the seating retrofit is very stiff, not allowing for the expected deformations under negative rotations.

Many existing seating angles have been designed without consideration of the above concerns. Factors such as flexibility in the anchor connection and probable versus design anchor capacities may show that existing angles are sufficient to support the floor in an earthquake event. Future research is needed to quantify these factors. Nevertheless, practitioners are encouraged to review existing seating retrofits that may have critical deficiencies, such as shallow embedded anchors with little capacity or stiff seating retrofits installed hard up against the soffit.

1.1 EFFECTIVENESS OF SEATING ANGLES

While seating angles are an appropriate retrofit option for LOS, observations from a recently conducted super-assembly test (Büker et al. 2022b) highlight that seating angles alone cannot effectively address PMF. The companion paper by Brooke et al. (2022) provides recommendations on which additional retrofit components are required to sufficiently address PMF.

Brooke et al. also discuss the failure hierarchy of precast concrete floors and its implication for the choice of retrofit techniques. It is emphasised that LOS may often be the governing failure mode as per seismic assessment (i.e. failure mode with the lowest assessed drift capacity), but it is not guaranteed that this failure mode occurs. Consequently, an adequate combination of floor retrofits needs to be installed that addresses all failure modes for which the drift demands exceed the assessed drift capacities.

This paper provides design and detailing recommendations for new seating angles. Two design approaches are outlined that mitigate the aforementioned concerns and ensure resilience to withstand demands during and after the earthquake.

2 RECOMMENDED SEATING ANGLE VARIATIONS

Recommendations for two approaches to design and detail seating angle retrofits for hollow-core floors are outlined in this paper. The first procedure allows the angle to be installed hard-up against the soffit of the floor, and the second procedure has the angle set down with a deformable infill strip. The conceptual details of these two solutions are illustrated in Figure 2. A key factor of the proposed seating angle details is to maximise the understanding of forces on the post-installed anchors. Modification of the proposed details may affect the design procedures outlined in this paper and requires careful consideration.

For the first design procedure, the seating angle is installed hard-up against the floor soffit, and thus, all components need to be designed and detailed to endure the earthquake-imposed deformations of the

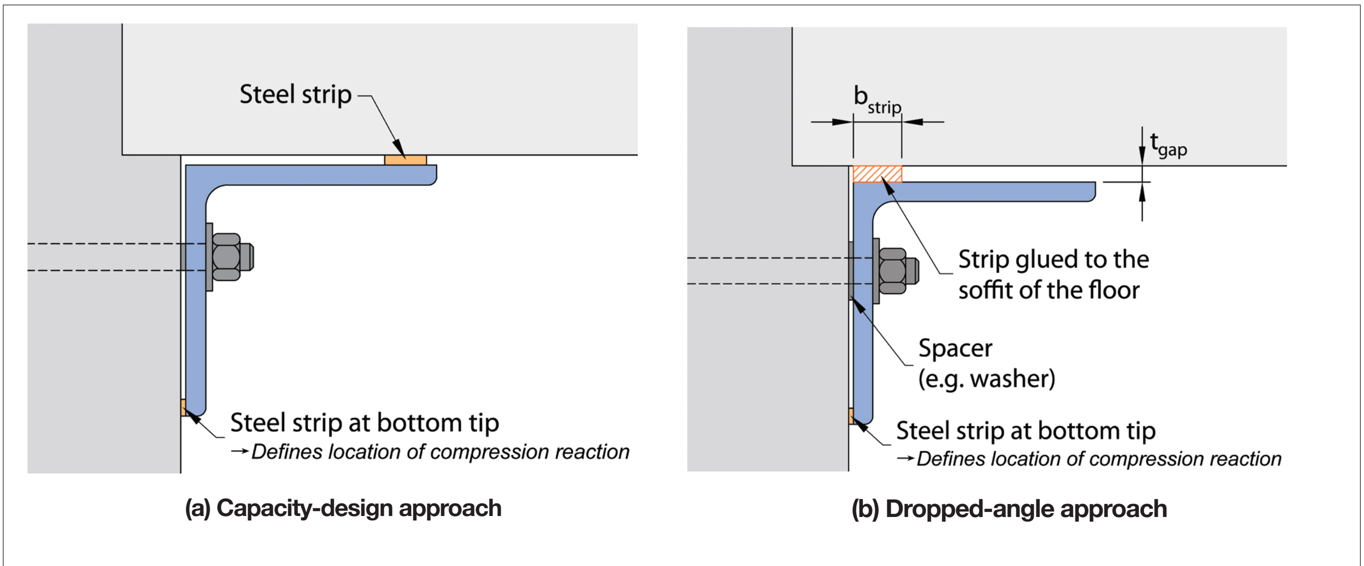

Figure 2: Detailing of the two recommended design approaches for seating angles

floor-to-support connection. As discussed in Section 1, these deformations can result in large force demands on the seating angle and the post-installed anchors. While ductile flexural behaviour can be expected from the steel angle, the post-installed anchors are likely to exhibit brittle performance when experiencing higher than expected demands. A 'capacity-design' procedure can be adopted to protect the post-installed anchors from overloading. Applying the concept of capacity design to the seating angle design ensures that an upper limit of the forces in the post-installed anchors can be determined from the flexural overstrength of the seating angle. The application of this design procedure is outlined in Section 3. To conduct the capacity-design procedure, the location of all applied forces must be known to reliably determine the shear and tension demands on the post-installed anchors. Therefore, steel bearing strips should be fixed (e.g. welded) near the toes of both legs, as demonstrated in Figure 2a. Other material could be used for the strip in lieu of the steel, provided it is stiff enough. It may be preferred to install a washer as a spacer between the beam face and back of the angle at the bolt connections for construction purposes, but such spacers are not crucial for the angle to perform as intended.

The advantage of the capacity-design approach is that there is no vertical drop once the floor unseats from its original support. This ensures that the diaphragm remains on the same level and may also limit additional damage to the floor, such as topping delamination or web-cracking.

The second detailing solution features a gap between the seating angle and the floor soffit and thereby avoids large forces in the anchors that could be generated by flexural deformation of the angle during negative support rotation. The detail incorporates a deformable infill strip of rubber or material of similar stiffness that is glued to the bottom of the floor, as shown in Figure 2b. The deformable infill strip can slide on the angle and ensures that the location of the vertical reaction is clearly defined. Furthermore, the deformable infill strip helps to limit the vertical drop of the floor and aids the installation process of the seating angle by ensuring a consistent gap to the floor soffit. Similarly to the capacity-design approach, a steel strip is recommended to be fixed (e.g. tack-welded) to the bottom toe of the vertical leg of the angle to ensure the location of the compression reaction is known.

A spacer in form of a washer or similar between the beam face and back of the angle at the bolt connections should be incorporated into the detailing

With this solution, the force demands on the anchors are generally lower compared to the capacity-design approach. Nonetheless, consideration should be given to the fact that, depending on the flexibility of the strip, the hollow-core unit will sustain a vertical drop if LOS occurs. This drop of the hollow-core unit can cause delamination of the floor topping and may promote web-cracking. The adverse effect of web-cracking on the floor performance and the gravity load-carrying capacity is currently not well understood. Furthermore, this solution has not been experimentally validated at the time of publication of this article. Consequently, the capacity-design method should be viewed as the preferred option.

Despite these recommendations exclusively covering the design of seating extensions using steel angle sections, it is also possible to use them, with slight modifications, to design supplemental seating employing rectangular hollow sections or other steel sections. In particular, for the capacity-design approach, some equations need to be modified to adjust for the different yield mechanisms of other sections.

2.1 LOAD COMBINATIONS

Precast floor retrofits need to be able to resist the loads that arise both during and after the earthquake. The load combinations outlined in this section are consistent with the overarching precast floor retrofit design recommendations outlined in the companion paper by Brooke et al. (2022).

Force demands during the earthquake can appropriately be represented by the ultimate limit state (ULS) load combination of permanent, earthquake and imposed actions as specified in NZS1170.0:2002-A5 (SNZ 2011):

$$E_d = \mathrm{G} + \psi_{\mathrm{E}}\mathrm{Q} + \psi_{\%\mathrm{NBS}}\mathrm{E}_{\mathrm{u}} \qquad (1)$$

where E_d is the design action effect, G is the permanent action (i.e. 'dead' load), ψ_{E} is the combination factor for earthquake action, Q is the imposed action ('live' load), $\psi_{\%\mathrm{NBS}}$ is a non-conventional notation reflecting the reduction of demands by the targeted %NBS rating and E_{u} is the earthquake action[1]. The area reduction factor, ψ_{a}, can be omitted as it is taken as 1.0 for one-way slabs.

Besides the force demands, it is essential to take into account the displacements and rotations imposed on the support connection and seating angle during the earthquake. These demands should be evaluated based on the relevant peak drift for the maximum considered earthquake (MCE) as specified in NZS3101:2006-A3 (SNZ 2017) under consideration of the targeted %NBS.

[1] Vertical accelerations can be neglected for the seating angle design due to their high-frequency

$$\psi_{\%NBS}\,\delta_{peak.MCE} = \frac{1.5}{S_p}\,\psi_{\%NBS}\,\delta_{ULS} \qquad (2)$$

where $\delta_{peak.MCE}$ is the peak MCE interstorey drift, S_p is the structural performance factor, δ_{ULS} is the ULS interstorey drift for the structure and all other variables have been defined previously.

In the post-earthquake scenario, the damaged floor must be able to support the gravity loads per NZS1170.0:2002-A5 (SNZ 2011):

$$E_d = 1.35G \qquad (3)$$

$$E_d = 1.2G + 1.5Q \qquad (4)$$

where all variables have been defined previously.

Designing the seating retrofit using the full ULS gravity load combination (Equations (3) and (4)) likely overestimates the actual load demands on the floor in a post-earthquake scenario. Brooke et al. (2022) argue that a reduction of the design live loads for the post-earthquake scenario may be reasonable on the basis that the damaged flooring units will have restricted access. In view of this argument, Equation (4) can be modified to:

$$E_d = 1.2G + 1.5\psi_E\,Q \qquad (5)$$

where all variables have been defined previously.

Seating retrofits of hollow-core units that are part of an egress route should not be designed with the reduced live loads but always with the full ULS gravity loads (Equations (3) and (4)) for the post-earthquake scenario. Furthermore, engineers and building owners should note that unrestricted usage of the floor is not possible after LOS has occurred if the retrofit is designed with Equation (5).

3 DESIGN RECOMMENDATIONS FOR THE 'CAPACITY-DESIGN' SOLUTION

The 'capacity-design' approach for seating angles has the objective to protect the post-installed anchors by designing them to resist the maximum expected loads associated with the flexural overstrength of the seating angle. This procedure aligns with the design provisions for post-installed anchors as per EN1992-4 (2018), which has superseded TR045 that NZS3101:2006-A3 (SNZ 2017) refers to for the design of post-installed anchors.

The capacity-design procedure involves the following four design steps:

1. Determine the required additional seating length, $\delta_{s,ret,CD)}$.
2. Size the seating angle for the flexural demands.
3. Check if the angle is expected to yield.
4. Capacity design the post-installed anchors.

The design procedure allows for two different design pathways based on whether the seating angle is expected to yield or remain elastic. These two pathways are illustrated in the flowchart shown in Figure 3. After determining the required additional seating length and sizing the angle to withstand the flexural demands, the expected rotation demands at the support can be compared to the rotation at which the seating angle starts yielding. If yielding of the seating angle is expected, 'Pathway 1' should be followed. The design assumptions in 'Pathway 1' use the conventional capacity-design philosophy by assuming that the seating angle may reach flexural overstrength.

In cases where the seating angle is not expected to yield, 'Pathway 2' can be followed. 'Pathway 2' provides the option to omit the overstrength factor, ϕ_{oms} and size the anchors for the nominal flexural strength of the angle, M_s, in recognition of the limited expected rotation demands. Nonetheless, it should be noted that 'Pathway 2' does not abide by the conventional rules of the capacity-design philosophy and, thereby, entails the risk of anchor failure if the earthquake is bigger than expected. 'Pathway 1' is applicable regardless of whether the angle will yield or not and is generally the preferred procedure for new retrofits. 'Pathway 2' may be more suitable for the reassessment of existing retrofits.

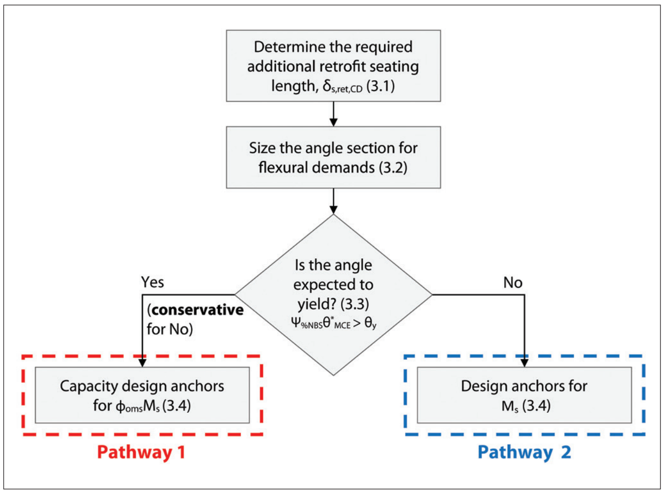

Figure 3: Flowchart of the design procedure for the capacity-design approach. Numbers in brackets refer to section numbers that follow.

The individual design steps for the capacity-design method are outlined in the following sub-sections.

3.1 REQUIRED SEATING LENGTH

The first design step is the determination of the additional retrofit seating length, $\delta_{s,ret,CD}$, that needs to be provided by the seating angle in addition to the existing seating. This length can be calculated as follows:

$$\delta_{s,ret,CD} \geq \delta_{s,\,NZS3101:2006A3} - \delta_{s,\,specified} \quad (6)$$

where $\delta_{s,ret,CD}$ is the additional available seating as shown in Figure 4, $\delta_{s,specified}$ is the seating length specified in the original drawing[2], and $\delta_{s,NZS3101:2006A3}$ is the theoretically required seating length for the existing hollow-core unit to sustain a maximum considered earthquake according to NZS3101:2006-A3 (SNZ 2017), which includes demands due to spalling, creep, shrinkage and thermal actions as well as tolerances in accordance with NZS3109:1997-A2 (SNZ 2004b).

Existing buildings may have uneven strengths at each end of the unit (i.e. strong, ductile starter bars at one support and non-ductile mesh at the other support), which may lead to a concentration of elongation at one end. On this basis, and as required by NZS 3101:2006-A3 (SNZ 2017), it is prudent to design the seating angle considering that the total elongation generated by the plastic hinges along the span of the unit concentrates at one end.

3.2 BENDING CAPACITY CHECK

Based on the required additional seating, an adequate steel angle section can be selected under consideration of the detailing recommendations discussed in Section 5. The bending capacity of the selected angle section should be sufficient to support the gravity loads of the floor during and after the earthquake. The demands during the earthquake consist of a vertical gravity load from the seismic weight of the floor (Equation (1)) and an associated friction force generated by the elongation movement, as depicted in Figure 5a.

After the earthquake, only a vertical load component remains (Figure 5b), but this component reflects the expected shear demands defined by the relevant post-earthquake load combinations (Equation (3) and Equation (4) or (5)). The yield line is expected to run horizontally along the upper edge of the nuts of the post-installed anchors, marked with a red dot in Figure 5.

For the bending design check, the design moment capacity, ϕM_s, should be equal to or larger than the maximum of the flexural demands imposed during and

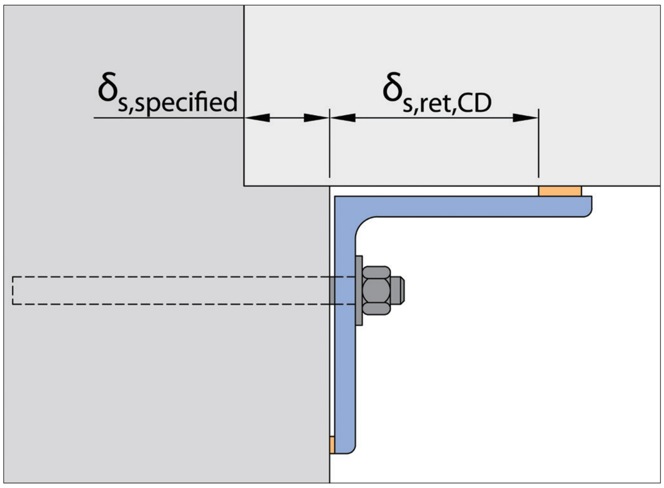

Figure 4: Required angle size to accommodate the seating demands.

after the earthquake:

$$\phi M_s \geq max \begin{pmatrix} V_{EQ}\ x_{1,CD} + \mu V_{EQ}\ y_{1,CD} \\ V_{post\_EQ}\ x_{1,CD} \end{pmatrix} \quad (7)$$

where ϕ is the strength reduction factor as specified in NZS3404:1997-A2 (SNZ 2007), M_s is the nominal section moment capacity based on NZS3404:1997-A2 (SNZ 2007), V_{EQ} is the ULS shear demand at the support during the earthquake calculated with Equation (1), μ is the friction coefficient between concrete and the strip, $y_{1,CD}$ is the vertical distance from the top of the nut to the top of the strip, V_{post_EQ} is the post-earthquake shear demand at the support calculated with Equation (3) or Equation (4) and $x_{1,CD}$ has been defined previously.

3.3 YIELD ROTATION CHECK

To find out which of the two design pathways can be used for the anchor design, the yield rotation of the angle must be determined and compared to the expected rotation demands. This design step can be omitted if the intention is to follow 'Pathway 1' regardless of whether the angle is expected to yield.

The floor-to-support rotation at which the angle is expected to yield can be calculated as:

$$\theta_y = \theta_{y,1} + \theta_{y,2} = \frac{2\varepsilon_\gamma}{t} y'_{1,CD} + \frac{2\varepsilon_\gamma (x'_{1,CD})^2}{3tx_{1,CD}} \quad (8)$$

where ε_γ is the yield strain of the steel grade used for the seating angle, t is the seating angle thickness, $y'_{1,CD}$ is the vertical distance between the top of the nut and the bottom edge of the root, $x_{1,CD}$ is the horizontal distance between the centreline of the strip to the centreline of the vertical leg of the angle section and $x'_{1,CD}$ is the horizontal distance from the centre of the strip to the edge of the root. The dimensions are also illustrated in Figure 6.

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[2] If the actual seating has been measured, $\delta_{s,specified}$ can be replaced by the actual seating length and tolerances, creep and shrinkage can be omitted from $\delta_{s,NZS3101:2006A3}$.

If the rotation demands are greater than the seating angle yield rotation, 'Pathway 1' must be followed. Otherwise, if the expected rotation demands are smaller or equal to the seating angle yield rotation, both 'Pathway 1' and 'Pathway 2' are valid.

$$\psi_{\%NBS}\theta_{peak,MCE} \begin{array}{l} \le \theta_y \rightarrow \textit{Pathway 1 or 2} \\ > \theta_y \rightarrow \textit{only Pathway 1} \end{array} \tag{9}$$

where $\psi_{\%NBS}\theta_{peak,MCE}$ is the floor-to-support rotation demand based on the peak MCE drift (Equation (2), factored by the targeted %NBS rating as defined in Equation (5) and θ_y is the floor-to-support rotation at which the angle is expected to yield as defined in Equation (8) . For a typical support arrangement in a strong-column weak-beam moment frame, the peak MCE floor-to-support rotation demand, $\theta_{peak,MCE}$, can be taken as equal to the peak MCE interstorey drift, $\delta_{peak,MCE}$.

3.4 CAPACITY DESIGN OF ANCHOR

The design loads of the anchors are determined following the capacity-design philosophy. Applying this philosophy to the seating angle configuration means that the angle must be able to accommodate the imposed demands during the earthquake through flexural deformations in a ductile manner. In order to prevent a brittle failure of the post-installed anchors, the anchors should be designed to withstand the upper-bound demands generated by bending of the angle. Therefore, it is recommended to keep the flexural demand to capacity ratio high when designing the seating angle for flexure because the greater the flexural strength of the seating angle, the higher the demands on the anchor.

The worst-case loading scenario for the post-installed anchors arises during negative support rotations when the interface shear resistance is still high. The forces

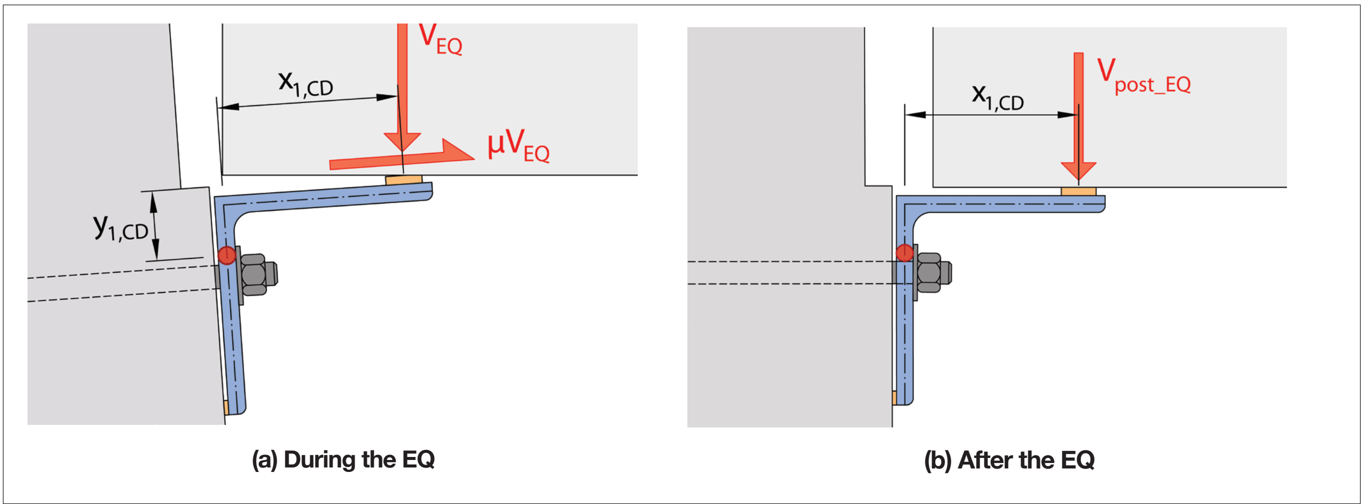

Figure 5: Bending checks of capacity-designed seating angle.

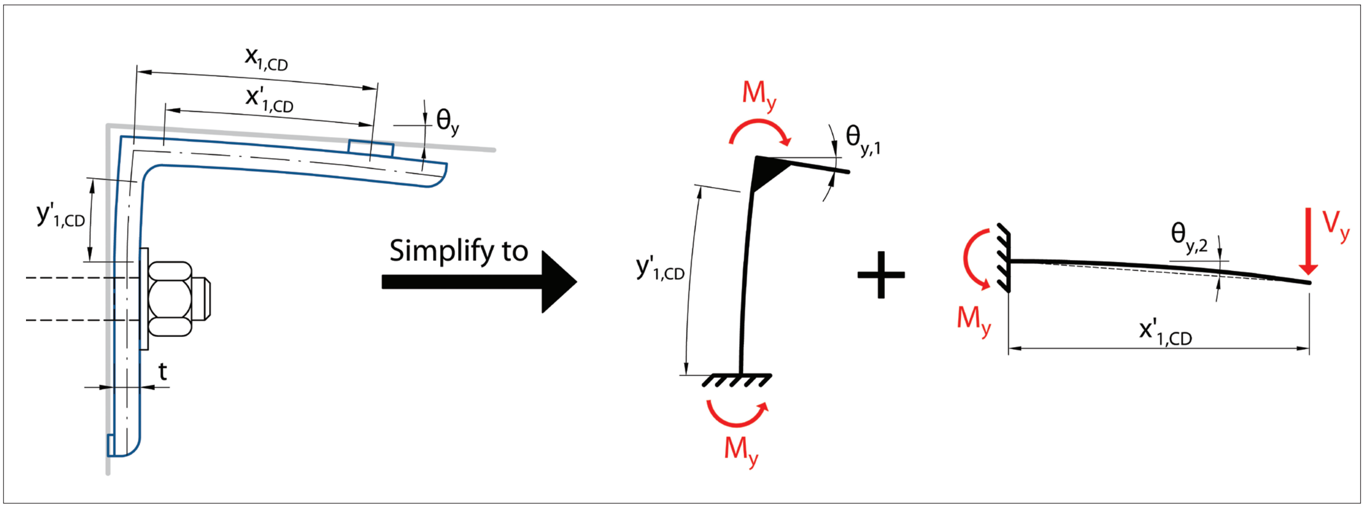

Figure 6: Estimation of the relative rotation between the supporting beam and the floor at which the angle starts yielding.

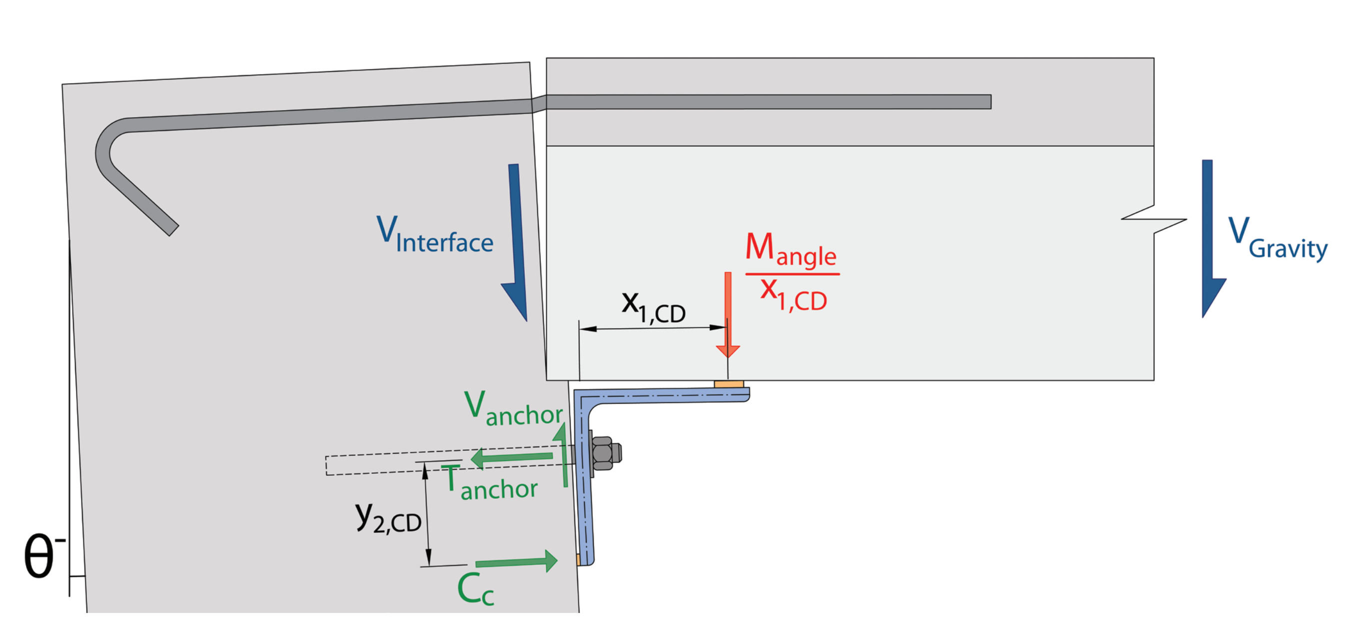

Figure 7: Capacity design of post-installed anchors.

acting on the seating angle assembly are shown in Figure 7. From the depicted scenario, the shear and tension demands on the post-installed anchors can be derived based on the flexural capacity of the seating angle:

$$V_{anchor} = \frac{M_{angle}}{x_{1,CD}} \tag{10}$$

$$T_{anchor} = \frac{M_{angle}}{y_{2,CD}} \tag{11}$$

where M_{angle} is the moment capacity of the seating angle at the top of the nut (for 'Pathway 1' use the overstrength moment capacity, $\phi_{oms}M_s$ as per NZS3404:1997-A2 (SNZ 2007), and for 'Pathway 2' use the unfactored nominal section moment capacity, M_s), $y_{2,CD}$ is the vertical distance between the centreline of the post-installed anchors and the centreline of the strip at the bottom toe of the angle and $x_{1,CD}$ has been defined previously.

Although the demands on the post-installed anchors are typically governed by the loading scenario elaborated above, the anchor capacity should also be evaluated for the forces generated by the floor sliding on the seating angle, in particular, in cases where the friction coefficient, μ, is high. For this loading scenario, which is depicted in Figure 8, the shear and tension demands on the anchors can be derived as:

$$V_{anchor} = V_{EQ} \tag{12}$$

$$T_{anchor} = \left(\frac{x_{1,CD} + \mu\, y_{3,CD}}{y_{2,CD}} + \mu\right) V_{EQ} \tag{13}$$

where $y_{3,CD}$ is the vertical distance from the anchor centreline to the top of the strip on the horizontal leg of the angle and all other parameters have been defined previously and are shown in Figure 8.

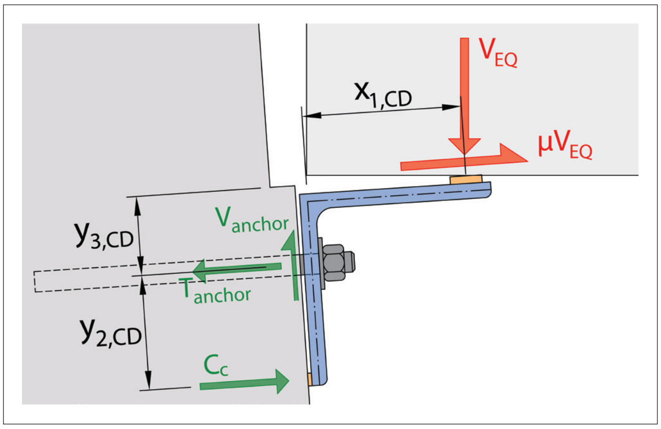

Figure 8: Forces in the post-installed anchors when the floor is sliding on the angle.

Seating angles designed with the capacity-design approach can be used in conjunction with the newly developed strongback retrofit discussed in the companion paper by Büker et al. (2022a). This retrofit combination was successfully tested in a super-assembly experiment recently conducted at the University of Canterbury (Büker et al. 2022b). When designing the seating angles for the strongback retrofit, modifications are required to the seating length check outlined in this Section 3.1. These modifications are described in the design recommendation for strongbacks (Büker et al. 2022a).

4 DESIGN RECOMMENDATIONS FOR THE 'DROPPED-ANGLE' APPROACH

As an alternative to the 'capacity-design' approach, the seating angle can also be designed using the 'dropped-angle' method. For this method, the seating angle is installed with a gap to the floor soffit and a deformable infill strip is glued to the floor, partially filling the gap as shown in Figure 2b. Installing the angle set-down has the advantage that demands on the post-installed anchors can be mitigated but, as discussed in Section 2, this method has several drawbacks, making it less reliable compared to the capacity-design solution.

The following sections outline the recommended design procedures for the dropped-angle approach. The naming convention of variables is kept consistent with the capacity-design approach, but for clarity, the subscript 'DA' for "dropped-angle" has been added.

4.1 REQUIRED SEATING LENGTH AND DESIGN OF THE STRIP

The deformable infill strip, fixed to the bottom of the hollow-core unit, needs to be fully supported on the seating angle even during large seating movements. To ensure the top leg of the seating angle has sufficient length, the earthquake-induced movements, namely the relative rotation between the support and the floor and beam elongation of the adjacent beam, need to be compared to the provided retrofit seating length, $\delta_{s,ret,DA}$:

$$\delta_{s,ret,DA} \geq \delta^*_{s,DA} \quad (14)$$

where $\delta_{s,ret,DA}$ is the additional seating length provided by the seating angle measured from the edge of the deformable infill strip to the tip of the seating angle as indicated in Figure 9, and $\delta^*_{s,DA}$ is the sum of the displacement demands due to the elongation of the adjacent beam and displacement induced by the rotation of the support beam as defined in the current concrete design standard NZS3101:2006-A3 (SNZ 2017). The total elongation from the plastic hinges along the floor span should be assumed to concentrate at one support when sizing the seating angle, as elaborated in Section 3.1. The effects of spalling, creep, shrinkage and construction tolerances do not need to be considered here.

In cases where hollow-core floors are exposed to significant thermal variation, such as parking decks, the displacements caused by temperature changes should be added to the earthquake demands.

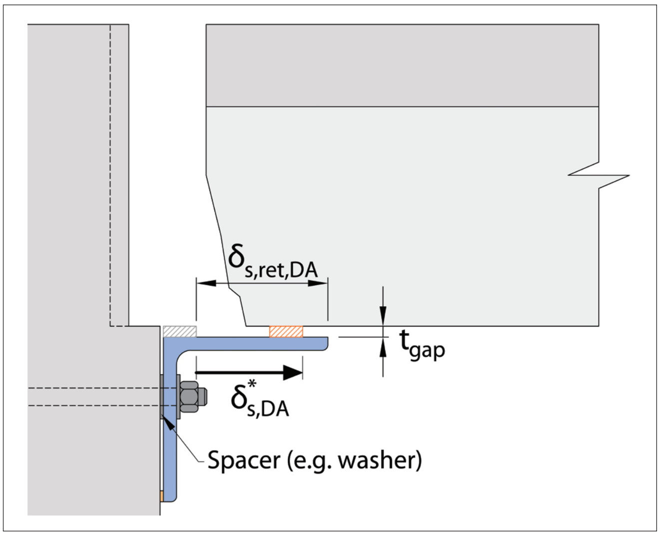

Figure 9: Required seating length for a dropped angle with deformable infill strip

The width of the gap between the seating angle and the floor soffit, t_{gap}, should generally be large enough so that the floor soffit does not come into contact with the tip of the horizontal leg of the angle during negative support rotation due to MCE peak inter-storey drifts (Equation (2)). To ensure that the angle is installed upright, a spacer (e.g. washer) should be added between the beam face and the back of the seating angle (Figure 9). If this spacer is intentionally omitted, the geometrical rotation resulting from the presence of the steel strip at the base of the vertical leg should be accounted for when sizing the gap, t_{gap}.

Considerations should also be given to the design and sizing of the deformable infill strip that is glued to the soffit of the floor. The recommended design and performance criteria for the deformable infill strip are as follows:

- The minimum recommended width of the deformable infill strip, b_{strip}, is 20 mm. A wider strip will generally provide more stability.
- The deformable infill strip should generally have the same length as the seating angle. However, if the seating angle is installed across several units, the deformable infill strip should be installed on a unit-by-unit basis.
- The choice of strip dimensions and material should be made under consideration of the following two criteria that ensure the strip performs as desired:
  - The deformable infill strip should be sufficiently stiff so that if the floor unseats and the strip

compresses under the floor loads, the tip of the angle does not come in contact with the bottom of the floor (Figure 10a). This scenario should be prevented because it is incompatible with the design procedures for the angle and anchor discussed in the following sub-sections. The material and dimension of the deformable infill strip should be selected so that this scenario will not occur. The deformation compatibility can be assessed geometrically assuming a scenario in which the floor-to-support connection is undergoing the maximum negative rotation (based on Equation (2)), and the floor has completely unseated, compressing the deformable infill strip under gravity load during the earthquake, V_{EQ} (based on Equation (1)). For simplicity, it can be assumed that the strip remains in the initial pre-earthquake position when unseating occurs. Alternatively, it is also valid to assume the likely location of the strip at the maximum negative rotation (based on Equation (2)) determined with the assessment guidelines C5 (MBIE et al. 2018) in lieu of NZS3101:2006-A3 (SNZ 2017) because it provides a more realistic estimate.

- The deformable infill strip should be flexible enough to prevent excessive force demands on the post-installed anchors. When the maximum negative support rotation occurs while the interface shear capacity is still high, forces can be transferred directly through the strip into the anchors, as demonstrated in Figure 10b. The magnitude of this force depends on the strain demand on the strip and can therefore be derived for the maximum negative support rotation pivoting about the front tip of the seating ledge. The anchor capacity should then be checked against this force demand. Note that for stiffer strips, the forces from this scenario may be the governing demands for the post-installed anchor design.

- An appropriate adhesive should be used for the fixation of the deformable infill strip to the bottom of the hollow-core unit. The adhesive must withstand the expected maximum friction force that is generated by the strip sliding on the seating angle during the earthquake (μV_{EQ}).

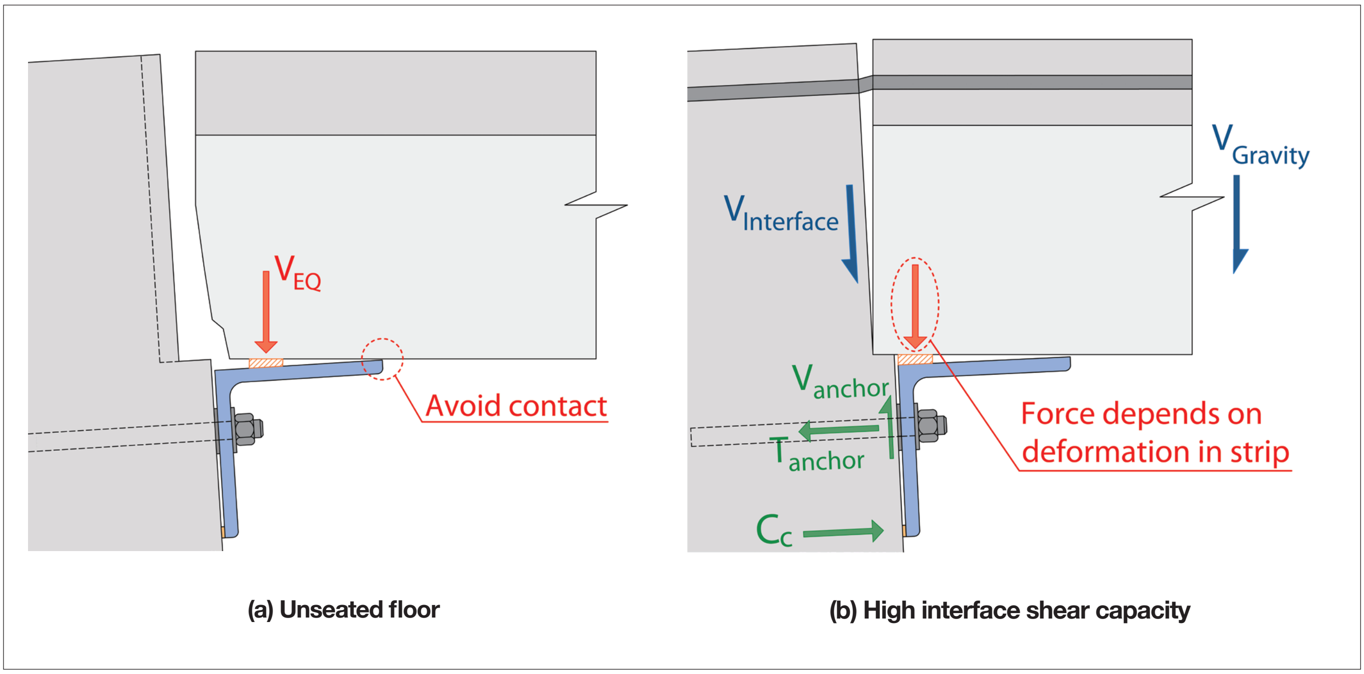

Figure 10: Scenarios to consider when sizing the deformable infill strip

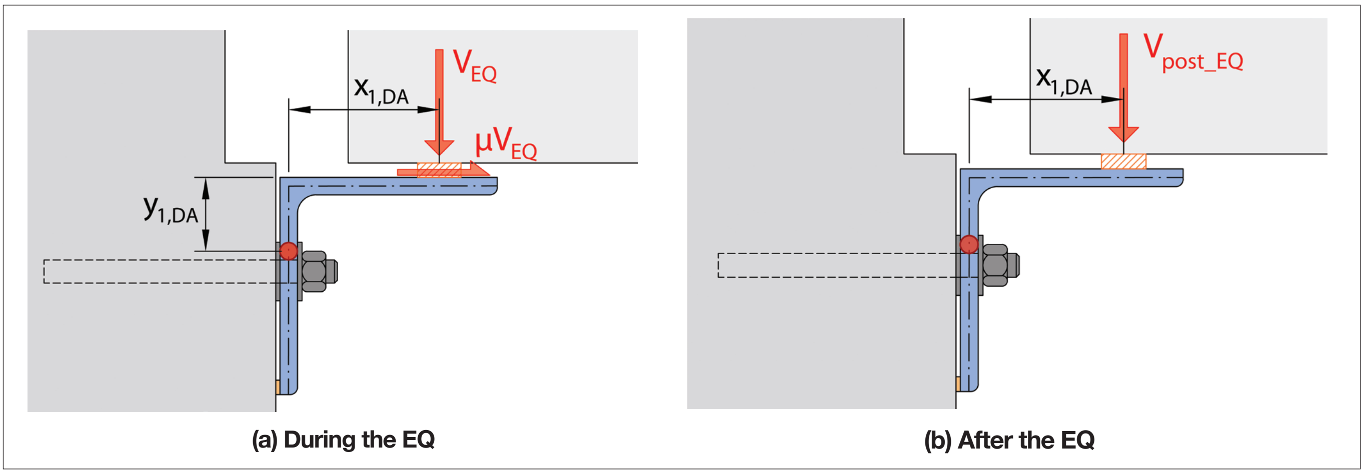

Figure 11: Bending check of a seating angle designed with the dropped-angle approach

4.2 BENDING CAPACITY CHECK

For the flexural design of the seating angle, both loading scenarios, during the earthquake (Figure 11a) and after the earthquake (Figure 11b), should be considered. The bending capacity of the angle section must be greater or equal to the maximum generated moment demand from these two scenarios:

$$\phi M_s \geq \max\begin{pmatrix} V_{EQ}\ x_{1,DA} + \mu V_{EQ}\ y_{1,DA} \\ V_{post\_EQ}\ x_{1,DA} \end{pmatrix} \qquad (15)$$

where ϕ is the strength reduction factor as specified in NZS3404:1997-A2 (SNZ 2007), M_s is the nominal section moment capacity based on NZS3404:1997-A2 (SNZ 2007), V_{EQ} is the ULS shear demand at the support during the earthquake calculated using Equation (1), $x_{1,DA}$ is the horizontal distance from the centreline of the deformable infill strip to the centreline of the vertical leg of the seating angle, μ is the coefficient of friction between the seating angle and the strip, $y_{1,DA}$ is the vertical distance between the top of the nut and the top of the seating angle and V_{post_EQ} is the post-earthquake shear demand at the support calculated using Equation (3) and Equations (4) or (5).

4.3 ANCHOR CAPACITY CHECK

By leaving a gap between the angle and the bottom of the floor, overloading of the anchors is prevented. Thus, tension and shear in the anchors are limited to the gravity demands during the earthquake (Figure 12a, Equations (16) and (18)) and after the earthquake (Figure 12b, Equations (17) and (19)):

During the earthquake

$$V_{anchor} = V_{EQ} \qquad (16)$$

$$T_{anchor} = \left(\frac{x_{1,DA} + \mu\ y_{3,DA}}{y_{2,DA}} + \mu\right) V_{EQ} \qquad (18)$$

After the earthquake

$$V_{anchor} = V_{post\_EQ} \qquad (17)$$

$$T_{anchor} = \frac{x_{1,DA}}{y_{2,DA}}\ V_{post\_EQ} \qquad (19)$$

where $y_{3,DA}$ is the vertical distance between the centreline of the post-installed anchors and the top of the angle and all other variables have been defined previously.

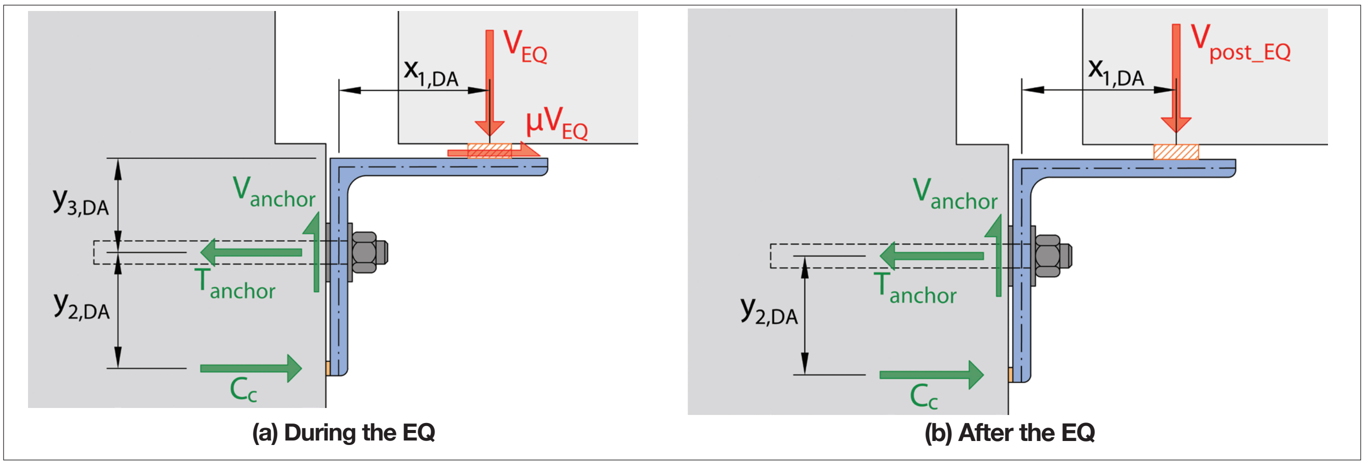

Figure 12: Forces in the post-installed anchors for the dropped-angle approach

The dropped-angle approach can be used in conjunction with the cable catch system tested in the recent super-assembly experiment at the University of Canterbury (Büker et al. 2021). When designing the seating angles to be used with the cable catch retrofit, stiffeners can be welded to the angles that act as fixing points for the cables. Due to the presence of these stiffeners, the capacity-design approach is not applicable. Nevertheless, demands on the anchors are likely governed by the tension forces generated in the cable when the floor drops onto the cable catches.

5 DETAILING AND LIMITATIONS OF SEATING ANGLES

Regardless of which seating angle design procedure is being followed, appropriate detailing is essential to ensure the seating angle performs appropriately. A list of detailing recommendations can be found below, with many of these recommendations also being applicable to other precast floor retrofits.

- A rigid connection between the seating angle and the hollow-core unit must be avoided to allow the flooring unit to slide freely on the seating retrofit and accommodate relative movement between the unit and the supporting beam.
- Holes in the seating angle provided for the post-installed anchors should be slotted parallel to the longitudinal axis of the angle. The reasoning for this recommendation is twofold. Slotted holes firstly make it easier to avoid drilling through existing beam reinforcement during anchor installation and secondly provide an allowance for relative movements between the anchors and the seating angle that are caused by flexural deformations and elongation of the support beam. To ensure sufficient nut-bearing along the slotted holes, wide and thick square washers should be used. A washer thickness of at least 5 mm is recommended.
- Chemical epoxy anchors are generally the default anchor solution for seating angles. Where feasible, more robustness in terms of anchorage can be achieved by drilling through the support member and anchoring the threaded rod on the other side of the support. This solution can be particularly appealing for internal support beams where the floors supported on each side require a seating extension retrofit. Note that this method still requires the filling of the hole with (optionally lower grade) epoxy or similar to stabilise the bar in the hole.
- Caution is needed when using anchors in regions where cracking is anticipated. Figure 13 indicates the following recommendations for the typical case of plastic hinges adjacent to columns (adjustments needed for gravity-dominated frames experiencing non-reversing plastic hinges within the beam span):
  - Anchors installed within half the beam depth away from the column are expected to be impacted by substantial cracking and should not be relied on to resist shear and tension demands (Figure 13).
  - For epoxy anchors installed within one beam depth away from the column, the cover concrete should not be relied on and should be discounted from the effective embedment depth.
- The seating angle should ideally cover all the webs, but this may not always be practical. A minimum support length of 900 mm (supporting five webs for a 200 mm deep hollow-core unit) is recommended. If the seating angle does not cover all webs, the shear capacity of the reduced number of supported webs should be checked against the design loads specified in this paper. Furthermore, to prevent instability and unwanted torsion demands, the angle should always be placed in line with the centreline of the hollow-core unit.

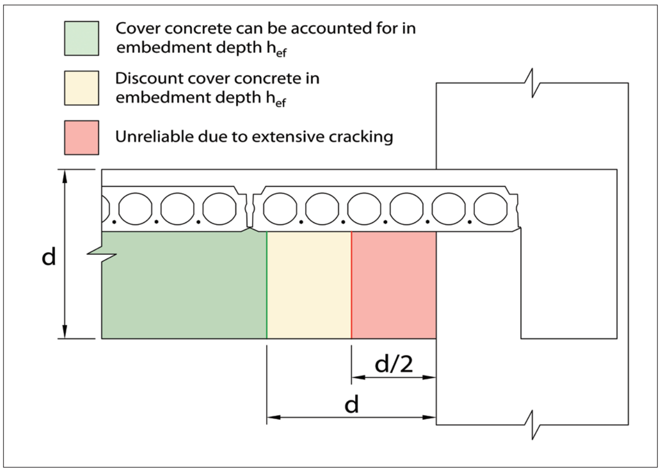

Figure 13: Anchorage in the plastic hinge region of the support beam

6 INFLUENCE OF THE SEATING ANGLE ON THE NEGATIVE MOMENT DEMANDS

With a seating angle installed hard up against the soffit of the hollow-core unit, the deformations of the seating angle during negative support rotations not only lead to large force demands in the post-installed anchors but also increased negative moment demands in the flooring unit itself. Parr et al. (2019) experimentally demonstrated that stiffened angles installed hard-up against the soffit are of particular concern and result in a significant increase in the negative moment demand, which can lead to NMF.

When designing the seating angle with the capacity-design approach, a certain degree of flexibility is assured through (1) the installation of bearing strips near the toes of the seating angle and (2) the incentive to limit the flexural strength and stiffness of the angle section to keep forces in the anchors low. In addition, the presence of the strips has the advantage that the location and upper limit of the force transferred into the floor by the seating angle can be determined with certainty. For seating angles installed without strips, both the location and the magnitude of the reaction at the top leg are challenging to determine, as elaborated in Section 1, and require additional research.

The increase in negative moment demand for capacity-designed seating angles may generally be low; nonetheless, a reassessment of the NMF vulnerability is necessary. Figure 14 demonstrates how to account for the additional negative moment demands induced on the floor. The moment demands in the flooring unit at the location of the bearing strip on the top leg of the angle can be determined as follows:

$$M_{o,angle\_tip} = M_{o,floor} + V_{end}\, x_{2,CD} - \frac{\omega x_{2,CD}^2}{2} \qquad (20)$$

where $M_{o,floor}$ is the overstrength moment at the back face of the hollow-core unit as defined for the NMF assessment in the assessment guidelines C5 (MBIE et al. 2018), V_{end} is the shear force at the back face of the hollow-core unit, which can be determined by solving the moment equilibrium about the opposite floor support, $x_{2,CD}$ is the distance from the back face of the hollow-core unit to the centre of the bearing strip at the top leg of the seating angle and ω is the gravity demand due to the un-factored self-weight (1.0G).

Parr et al. (2019) also showed that a potential increased NMF vulnerability can be counteracted by increasing the negative moment resistance through post-installing rebars into the topping concrete. Alternatively, to avoid

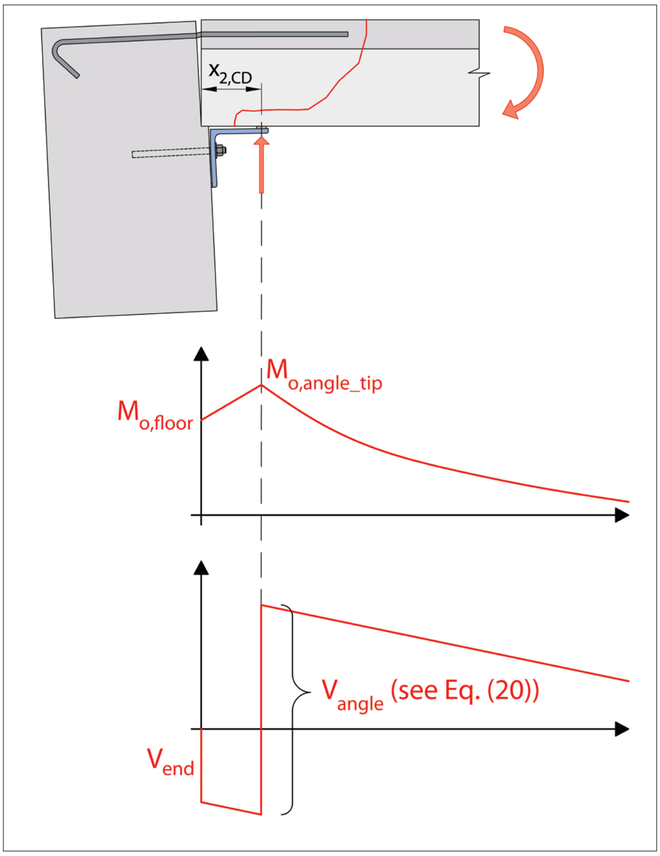

Figure 14: The influence of a seating angle on the negative moment demands.

the effect of increased negative moment demands, the dropped-angle approach can be used.

7 CONCLUSIONS

Seating angles are a widely used retrofit solution to protect hollow-core floors against unseating during earthquakes. In this paper, concerns are raised about the appropriateness of the common design and detailing approach for seating angles, such as the uncertainty of the post-installed anchor demands generated by earthquake-imposed deformations.

Two design approaches for seating angles that aim to address these concerns are outlined in this paper. The first solution referred to as the ‘capacity-design’ approach, allows the seating angle to be installed hard-up against the soffit of the floor. A capacity-design philosophy is adopted to protect the post-installed anchors from being overloaded. The second solution, referred to as the ‘dropped-angle’ approach, avoids high anchor demands during negative support rotation by installing the seating angle with a gap to the hollow-core floor soffit and adding a deformable infill strip of rubber or similar material.

Both solutions are viable design approaches, but the capacity-design approach is the preferred option because it ensures that the diaphragm remains on the same level and reduces the likelihood of delamination or web splitting. Also, a determinate and desirable hierarchy of failure is achieved using the 'capacity-design' approach. When designing the angle using the dropped-angle approach, it needs to be anticipated that a small drop of the floor could be sustained, with the potential consequence of promoting topping delamination and web-cracking.

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