THE CONCRETE NZ CONFERENCE 2018
PROGRESS THROUGH COLLABORATION
Claudelands, Hamilton | 11 – 13 October 2018

NEW APPENDIX TO SECTION C5 OF THE "SEISMIC ASSESSMENT OF EXISTING BUILDINGS" FOR ASSESSMENT OF PRECAST FLOORS

KEN ELWOOD[1], DES BULL[2], CARL ASHBY[3], ALISTAIR RUSSELL[2], RAY PATTON[4], CHRIS POLAND[4]

[1] University of Auckland
[2] Holmes Consulting
[3] WSP Opus International
[4] Clendon Burns and Park Ltd

SUMMARY

In July 2017, MBIE, SESOC, NZSEE, and NZGS released the first edition of the *The Seismic Assessment of Existing Buildings (the Guidelines)*. Part C of the *Guidelines* describes the Detailed Seismic Assessment (DSA) process used to assess the seismic behaviour of a building. Section C5 provides recommendations for the assessment of concrete buildings, with Appendix C5G describing the assessment of precast concrete floor systems, though principally by reference to other publications. Appendix C5G was rewritten in the year following the initial release of the Guidelines to address a recommendation from the Statistics House Investigation (MBIE 2017) that:
"MBIE develop guidance for practicing engineers and other building professionals to assist them to assess existing multi-story ductile buildings constructed with pre-cast floor systems; specifically, flooring systems identified as being prone to the effects of beam elongation during a significant earthquake."

This paper provides a summary of the proposed revision to Appendix C5G, Assessing Precast Concrete Floor Systems. Building on the assessment procedures of Fenwick et al (2010), this revision will improve the usability, coverage, and realism of the Guidelines. It is anticipated that this will lead to more consistent and accurate assessments of the capacity of existing precast concrete floors. (Appendix section numbers are used in this paper to help navigation of the Appendix although the reader should note that editing of the Section C5 at the time of publication of this paper may result in changes of these specific section numbers, including the label for the Appendix itself.) This paper is only a high-level summary of the Appendix and should not be used to do seismic assessments.

INTRODUCTION

Precast concrete hollowcore, double-tee, rib and infill, and flat slab floor units are all seated on ledges formed in their supporting beams as illustrated in Figure 1(a). Unseating can occur during earthquake shaking due to frame or wall elongation, supporting beam rotation, and/or spalling of the support ledge and unit. Diaphragm action is achieved through the use of an in-situ reinforced concrete topping, typically with starter bars connecting to the support beams. This arrangement can provide rotational restraint at the ends of the units which can lead to damage to the units, compromising gravity load support, unless modern support detailing is provided (NZS 3101:2006 detailing with low friction bearing strip). For buildings with older support detailing, the limiting drift at failure of the precast floors is likely to be less than the limiting drift for the frame and may govern the earthquake rating for the building as a whole.

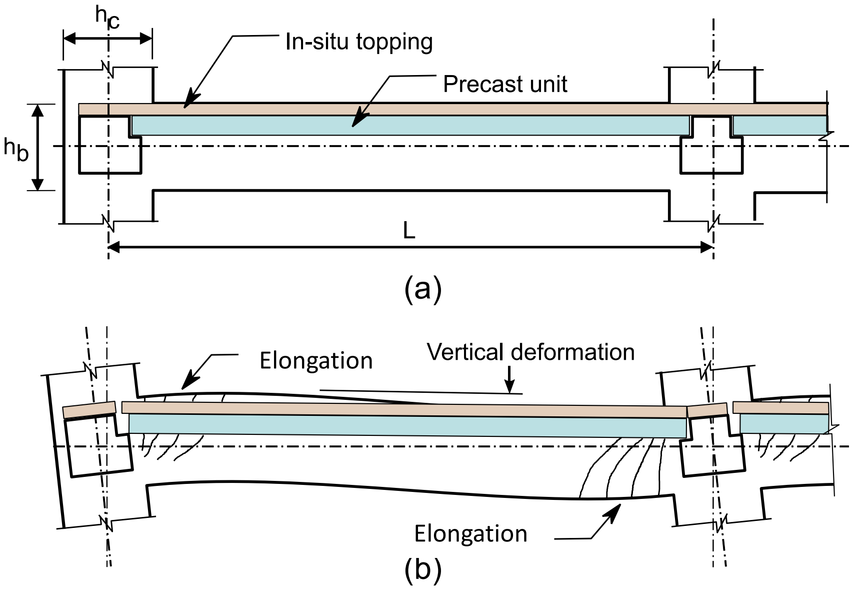


Figure 1: Section through precast concrete floor units illustrating (a) its construction and (b) elongation of beams alongside the floor units

Appendix C5G focuses on identifying the drift demands in the primary structure that are likely to cause all or part of a precast unit to lose gravity load support. It is noted that unreliable load paths (e.g. jamming of units, tension across topping to unit interface, etc.) may result in gravity load support for units beyond the drifts indicated by this appendix; however, such load paths cannot be reliably calculated or depended on to always be present and hence are ignored in the recommended assessment process. Methods are provided for assessing the limiting drift capacity for the following failure modes, depending on the type of precast floor units:

Hollowcore floor units:

1. Loss of support
2. Negative moment failure at end of starters
3. Positive moment failure and web cracking

Double tee units:

1. Loss of support
2. Flexural failure of flange-hung double-tee floor units

Rib and infill:

1. Loss of Support
2. Positive moment failure
3. Negative moment failure at the end of the starters

Flat Slab units:

1. Loss of support
2. Negative moment failure at end of starters
3. Positive moment failure and web cracking

Rib and infill systems benefit from more integral construction and thicker slab uniformly across the floor. It is noted that rib and infill systems can potentially develop secondary load paths for gravity loads even if ribs experience failures. The secondary load paths arise from the increased thickness of the cast-in-place portion of the floor system and the improved bond with the ribs through closed stirrups.

All forms of damage assessed in this Appendix can lead to a significant life safety hazard (see Part A, *Seismic Assessment of Existing Buildings, July2017*) should a precast floor unit or a significant part of a unit become detached and fall. Such failures are sudden and brittle. As indicated in Section C5, when assessing brittle failure modes of precast concrete components the peak displacements determined from the analysis of the primary lateral load resisting system should be increased by $1/S_p$, where the value of S_p is that used in the analysis of the primary lateral load resisting system. However, precast floors assessed using the criteria in this appendix need not be considered a Severe Structural Weakness (SSW).

Precast floors, connected by a topping, also serve as diaphragms to distribute inertial forces to the primary lateral systems. Diaphragm demands and capacities are assessed in accordance with Section C5 of the Guidelines.

Assessments should be undertaken according to NZS 3101 except as noted in the Appendix. Since NZS 3101 is intended for new design, it may be more conservative than is appropriate to achieve the intent of the Guidelines as defined in Part A.

INSPECTING PRECAST CONCRETE FLOOR SYSTEMS

Section C5G.2 describes considerations that must be made during site inspections. Engineers are expected to identify the systems, sub-systems, elements, members and connections, as described in Section C1. They should then use an appropriate level of inspection to determine the condition of the precast floor system. This may require removal of floor coverings and intrusive work in ceilings and wall cavities to investigate and record the relevant details and damage from past earthquakes or other causes.

Buildings have a large numbers of precast concrete floor panels. The inspection and investigation programme therefore needs to identify the locations where the panels are likely to be subjected to demands (forces and deformations) from past earthquakes that could have resulted in damage or exceeded their capacity. These locations will normally be at floor levels developing largest inter-storey drifts as calculated using Section C2, and include floor plan corners where deformation incompatibility and beam elongation can lead to higher demands on precast floor units. A statistically valid sample of the panels needs to be inspected, including locations where their capacity is considered unlikely to be exceeded. Engineers should relate any identified damage to the critical damage states described in Henry et al (2017).

Identification of the seating and end embedment details, and the locations and sizes of cracks developed by shrinkage, creep, curtailed reinforcing, and service actions are important for all three types of precast floor systems because they can significantly affect their seismic performance. The inspection will normally verify and augment the construction drawing details. The following aspects requiring careful inspection are common to all three flooring systems:

- Whether units span past columns or between columns
- the presence and geometry of starter bars or continuity reinforcement that could resist relative movement of the supporting beam and precast unit
- cracking of the concrete topping at the ends of the precast units or curtailed reinforcing
- debonding between the precast unit and topping
- the condition of the ends of the precast units, including:
  - transverse or corner cracking on the soffit
  - loss of prestressing (i.e. retraction of the tendon ends)

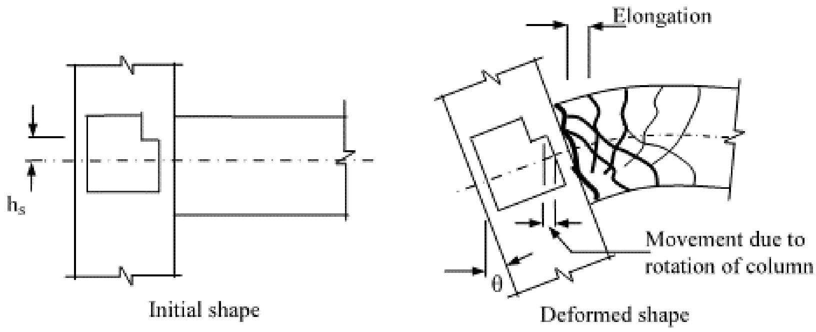
- the geometry, reinforcing, armouring, and condition (especially spalling) of the supporting ledges
- construction gaps that will reduce seating widths
- dimensions of any low-friction seating strips or mortar pads
- flooring system-specific features listed in the subsections below

Specific issues and details that should be looked for pertaining to the four common precast concrete floor unit types (hollowcore, double tee, rib and infill, and flat slab) are provided.

DEFORMATIONS IMPOSED ON PRECAST FLOOR SYSTEMS

Precast floor systems must be able to accommodate deformations imposed by the supporting structural system. The Appendix provides guidance on estimating deformations arising from beam elongation and rotation expected in moment resisting frames and deformations imposed on precast floor systems in wall buildings.

Elongation of plastic hinges can push beams supporting precast floor units apart and reduce the contact length between the precast units and support ledge. However, as elongation is related to the mid-depth of the beam containing the plastic hinge it is also necessary to allow for further movement between precast units and support ledge due to rotation of the supporting beam as illustrated in Figure 2.



Movement of support relative to precast unit equals elongation of beam plus column rotation, θ, times height between beam centre-line and support seat, h_s

Figure 2: Displacement at support of precast unit due to elongation and rotation of support beam (Fenwick et al., 2010)

Experimental testing on structures with precast floor units has demonstrated that frame elongation is partially restrained by precast concrete floor units when they span parallel to the beams. Experience from Canterbury and Kaikōura Earthquakes confirms that the greatest elongation occurs at the beams framing into the corner columns, and considerably less elongation for beams framing into internal beam-column joints.

NZS 3101:2006 (A3) provides estimates for the elongation of reinforced concrete plastic hinge based on total beam rotation demand. Marder et al (2018) have demonstrated that use of total rotations provides a conservative estimate of the beam elongation appropriate for design of new buildings. For assessment, where estimates of expected or mean demands are desired, it is more appropriate to use plastic rotations in place of total rotations when estimating beam elongation. The Appendix recommends estimating the beam elongation based on the equations of NZS 3101:2006 (A3) with plastic rotation demand replacing the total rotation demand.

The Appendix also provides guidance on how to attribute the total beam elongation to the ends of the precast floor unit being assessed. Units immediately adjacent to the elongating beam will need to accommodate all of the expected elongation. Observation from past earthquakes indicates that the elongation demands diminish the further the unit is away from the elongating beam. The Appendix defines an “elongation zone”, l_e, where the effects of elongation must be considered. Outside this zone, deformation demand for assessment are based only on rotation of the supporting beam.

The “elongation zone” is specified for assessment of an unretrofitted building. It is strongly recommended that retrofits for seating be provided over the full length of the supporting beam if required at any point along the beam.

INTER-STOREY DRIFT CAPACITY OF HOLLOWCORE FLOOR SYSTEMS

The procedure for determining inter-storey drift capacity hollowcore floor systems is shown in Figure 3. The drift capacity of hollowcore floor systems is governed by loss of support (LoS), failure of the unit within the negative moment region (Negative Moment Failure - NMF), or failure due to positive moment cracks near the support (Positive Moment Failure – PMF).

Positive Moment Failures can be suppressed if the seating for the hollowcore unit uses low friction bearing strips as required by Amendment 3 to NZS 3101:1995 (published in April 2004). If such support details are not included, the end of the unit is likely to be trapped in the supporting beam and relative rotation of the supporting beam will result in a positive moment crack near the support. Beam elongation and support beam rotation must be accommodated at the positive moment crack. Collapse of all or part of the unit can result if the positive moment crack exceeds the specified critical crack limit or if the positive moment crack is also accompanied by web splitting.

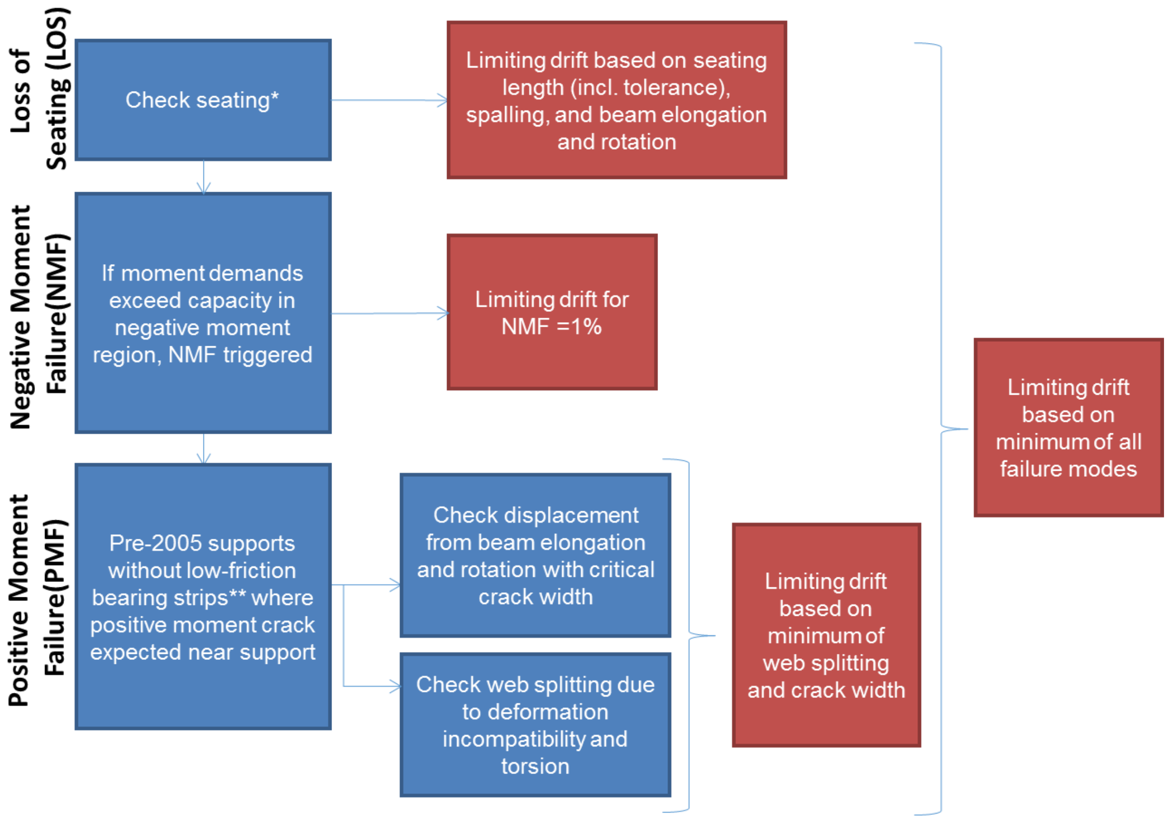
When assessing the adequacy of existing seating widths for loss of the support, the following needs to be considered as defined in the Appendix:

1. movement of precast floor unit units relative to the ledge providing support due to elongation and rotation of support beams
2. inadequate allowance for construction tolerance
3. spalling of concrete from the front face of support ledge and back face of the precast floor unit
4. creep, shrinkage and thermal movement of the floor, and
5. crushing of concrete resisting the support reaction due to bearing failure.

Loss of support need not be checked if supplemental support for seismic weight can be provided by 30-degree kinking of R16 bars anchored and detailed in alternating hollowcore cells as specified in C18.6.7 of NZS 3101:2006 (A3).

Where the end of the unit is fixed into the support by the topping reinforcement or by other continuity reinforcement, a negative moment may be induced and cracks can occur. Where the starter reinforcement has been terminated close to the support, a critical section for negative flexure may occur at the cut-off point, where the moment capacity reduces over the development length. The moment demand may exceed the moment capacity at that region. Note that units with paperclip reinforcement in broken out cells are particularly prone to Negative Moment Failure due to the high flexural capacity at the end of the unit. This failure was observed in tests by Liew (2004).

Experimental evidence indicates negative moment failures can occur at drifts at or below 2% for cases where elongation is not imposed (Liew 2004). A limiting drift of 1% is recommended in the Appendix for any cases where the moment demands at the end of the starters exceeds the moment capacity to account for the presence of elongation, as well as other factors impacting the capacity of units in real buildings not accounted for in the experiments including vertical ground acceleration, torsion of units, etc.



* Loss of Seating need not be checked if supplemental support for seismic weight can be provided by 30-degree kinking of two R16 bars anchored as specified in C18.6.7 of NZS 3101:2006 A3

** For supports with low-friction bearing strips designed to Amendment 3 to NZS 3101:1995 (published in April 2004) , positive moment crack can be assumed to be suppressed and checks for web splitting and positive moment crack width can be ignored.

Figure 3 – Procedure for determining inter-storey drift capacity hollowcore floor systems

INTER-STOREY DRIFT CAPACITY OF DOUBLE-TEE FLOOR SYSTEMS

Precast double tee units can be supported either on the flange or web, and for both types a critical failure due to loss of seating length needs to be checked. Flange hung double tee units in existing New Zealand buildings were predominantly detailed using the “loop bar” (or “pig-tail”) support detail. For flange-hung units an additional check needs to be made for a flexural failure at end of supporting flange. See Figure 4.

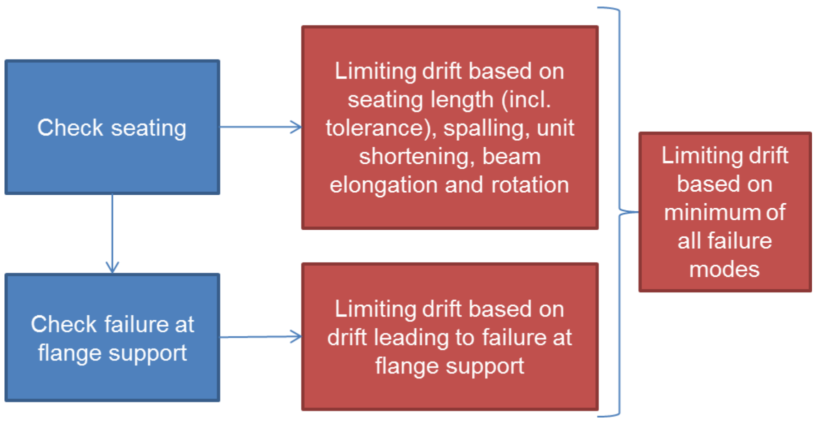


Figure 4 – Procedure for determining inter-storey drift capacity of double-tee floor systems

This section assumes a double tee unit contains shear reinforcement, and therefore, is typically not susceptible to negative moment failure. An assessment process similar to that recommended for hollowcore should be followed if shear reinforcement is not present.

Furthermore, web-supported double tee units with webs trapped in cast-in-place concrete from supporting beam should be assessed for positive moment failure using a method similar to that recommended for ribs.

INTERSTOREY DRIFT CAPACITY OF RIB AND INFILL FLOORS

The drift capacity of rib and infill floors differs from hollowcore floors in that not all of the identified failure modes are applicable. The increased flexibility of rib and timber infill floors in comparison to hollowcore units means that the failure modes resulting from the stiff, box sectional behaviour of hollowcore units (failure due to incompatible displacements and torsional failure) do not need to be considered.

The presence of shear reinforcement between the ribs and insitu slab may also allow for a reliable secondary load path after failure of a limited number of ribs has initiated (see Figure 5). These secondary load paths include the catenary action of kinked starter bars bearing on the rib stirrups and load sharing between adjacent ribs. These secondary load paths are considered reliable as delamination from the insitu slab is less likely to occur for ribs where transverse reinforcement provides a better connection between the insitu topping and the unit compared to either hollowcore or double tees. Such connection is not available in hollowcore, double tees, or ribs without stirrups extending into the insitu topping, and hence reliable secondary load paths are only considered for assessment of ribs with stirrups at the ends of the units. Guidance regarding assessment of the secondary load paths in rib and infill systems is also provided.

INTERSTOREY DRIFT CAPACITY OF FLAT SLAB FLOORS

As with rib and timber infill floors, the drift capacity of flat slabs floors differs from hollowcore floors in that not all of the identified failure modes are applicable. The shorter spans and shallower depths in comparison to hollowcore units means that the failure modes resulting from the stiff, box sectional behaviour of hollowcore units (failure due to incompatible displacements and torsional failure) do not need to be considered.

A procedure for determining inter-storey drift capacity of flat slab systems is shown in Figure 6.

CONCLUSIONS

This paper provided a brief overview of the proposed revision to Appendix C5G, Assessing Precast Concrete Floor Systems, of the Seismic Assessment Guidelines released in July 2017. The proposed revision provides procedures appropriate for application in engineering practice, coverage of all precast floor systems used in New Zealand, and updates the July 2017 version based on observations from the Kaikoura earthquake. Furthermore, the modifications have been validated using available experimental data.

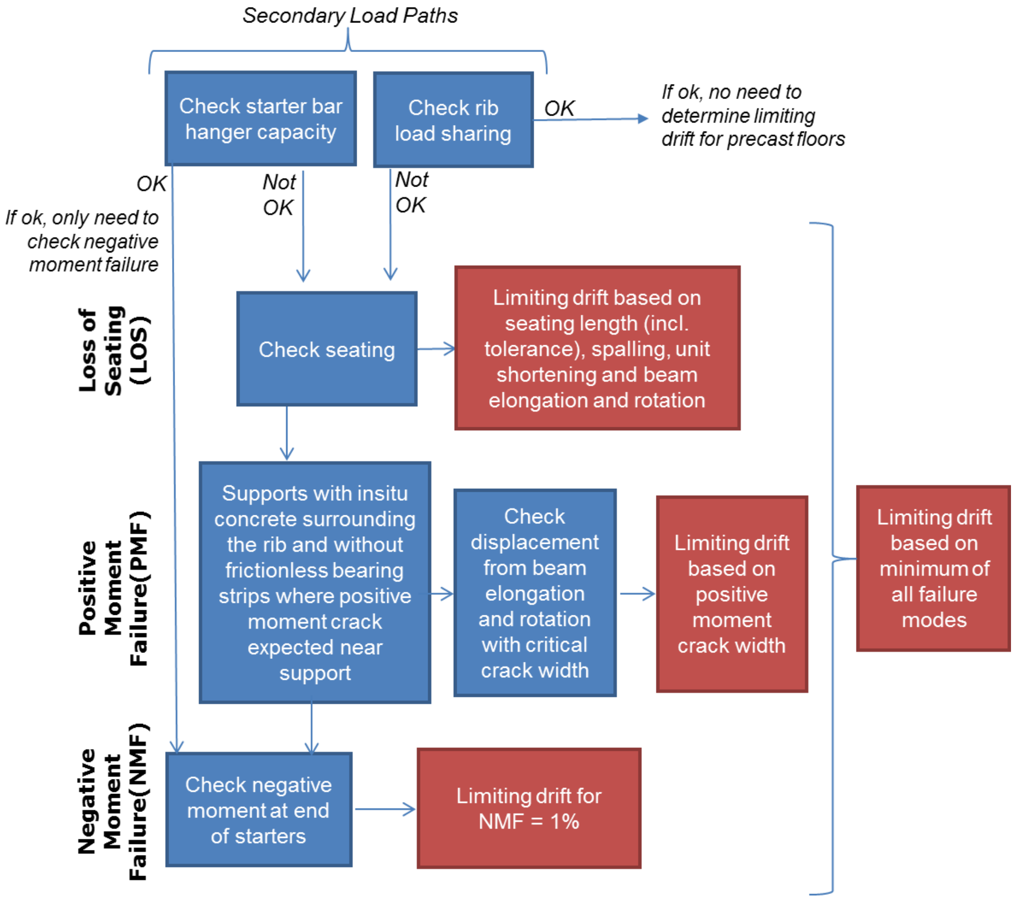
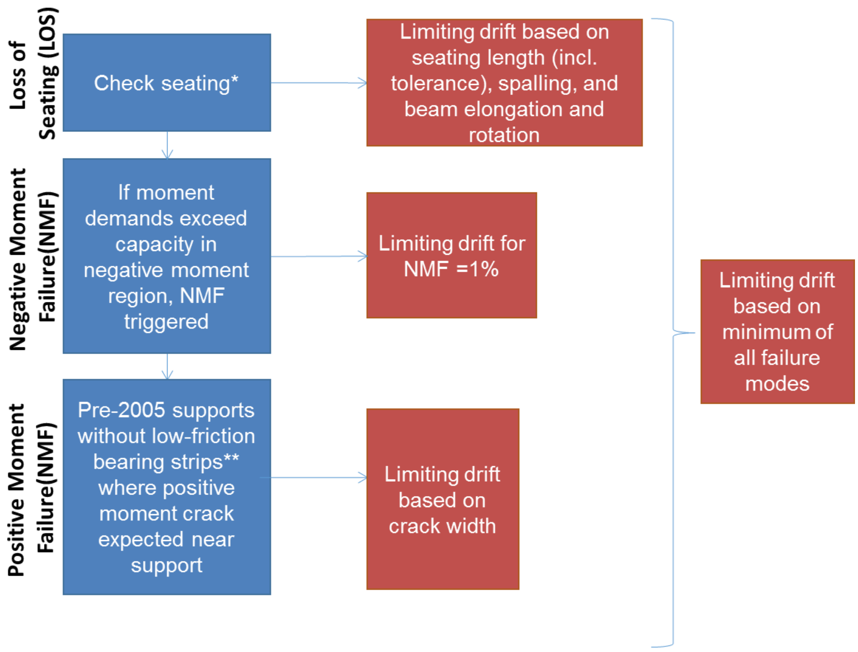


Figure 5 – Procedure for determining inter-storey drift capacity of rib and timber systems



* *Loss of Seating need not be checked if supplemental support for seismic weight can be provided by 30-degree kinking of two R16 bars anchored as specified in C18.6.7 of NZS 3101:2006 A3*

** *For supports with low-friction bearing strips designed to Amendment 3 to NZS 3101:1995 (published in April 2004) , positive moment crack can be assumed to be suppressed and checks for web splitting and positive moment crack width can be ignored.*

Figure 6 – Procedure for determining inter-storey drift capacity of flat slab systems

REFERENCES

Fenwick, R. C., Bull, D. K., and Gardiner, D. R. (2010). *Assessment of Hollow-Core Floors for Seismic Performance* (Research Report 2010-02). Department of Civil and Natural Resources Engineering, The University of Canterbury, Christchurch, New Zealand, 152p.

Henry, R. S., Dizhur, D., Elwood, K. J., Hare, J., and Brunsdon, D. (2017). “Damage to Concrete Buildings with Precast Floors During the 2016 Kaikoura Earthquake.” *Bulletin of the New Zealand Society for Earthquake Engineering*, 50(2), pp.174–186.

Liew, HY, (2004) “Performance of Hollowcore Floor Seating Connection Details”, University of Canterbury, ME Thesis.

Marder, K., Motter, C., Elwood, KJ, and Clifton, G.C. (2018) “Testing of Seventeen Identical Ductile Reinforced Concrete Beams with Various Loading Protocols and Boundary Conditions” Earthquake Spectra, doi.org/10.1193/101717EQS215DP.

MBIE. (2017). *Investigation into the Performance of Statistics House in the 14 November 2016 Kaikoura Earthquake*. Ministry of Business, Innovation, and Employment, Wellington, New Zealand, 36p.

NZS 3101. (2017). *Concrete Structures Standard* (NZS 3101:2006 inc. A1-A3). Standards New Zealand, Wellington, New Zealand.

NZSEE, MBIE, EQC, NZGS, and SESOC. (2017). *The Seismic Assessment of Existing Buildings: Technical Guidelines for Engineering Assessments* (Technical Guidelines for Engineering Assessments). Ministry of Business, Innovation, and Employment, Wellington, New Zealand.