Report to the Royal Commission

Stairs and Access Ramps between Floors in Multi-storey Buildings

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1.0 Background

The Darfield earthquake of the 4 September, 2010 and the Lyttleton earthquake of the 22 February, 2011, have produced less than desirable performances of a number of stairs and ramps. Stairs collapsed in at least 4 multi-storey buildings and in many other cases the stairs sustained serious damage. Both concrete and steel stairs were seriously damaged, and this has necessitated the review of current design practices and recommendations for designers to improve the performance of stairs and ramps, both for assessment of existing stairs and the design of future stairs.

Stairs, in particular, are critical in the safe evacuation of buildings. In the case of major earthquakes, the stairs and ramps can be exposed to forces and displacements significantly more severe than those of everyday loads. During earthquakes the floors move horizontally, relative to each other, known as "interstorey drift".

Review of current and previous Loading Standards shows that interstorey drifts that stairs need to sustain are underestimated in current (2011) and previous Standards. This is clearly one of the reasons for the observed collapses.

Inadequate assessment of inter-storey drift in earthquakes may result in either;

- The stiffness of the buildings being locally increased by the stairs transferring forces between floors. The resultant interaction between the stairs and other structural elements may cause the building to deform in ways that were not envisaged by the designer. For example the added local strength and stiffness may introduced higher structural actions into elements causing a non-ductile failure to occur, or alternatively the change in stiffness may induce adverse torsional displacements, about the vertical axis of the building, which cause premature failure of columns due to the increased deformation imposed on them;
- The structural actions induced in the stairs may cause the stairs to collapse or the forces transferred to the landings may cause these elements to fail;
- The stairs may lose support and collapse.

2.0 Structural Actions of Stairs

There are three main sets of actions applied to stairs and ramps that need to be considered.

The first was typically considered by the designer, which is the relative displacement between adjacent floors, the "interstorey drift", along the main axis of the stair. However, as described below, both the magnitude and directions of the interstorey drift are either underestimated or not considered in design.

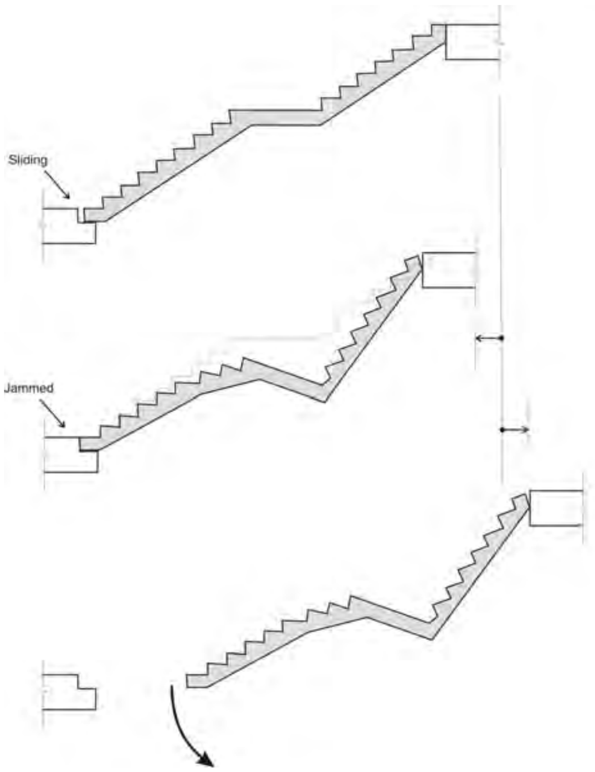
1) Interstorey drift along the main axis of the stair or ramp:

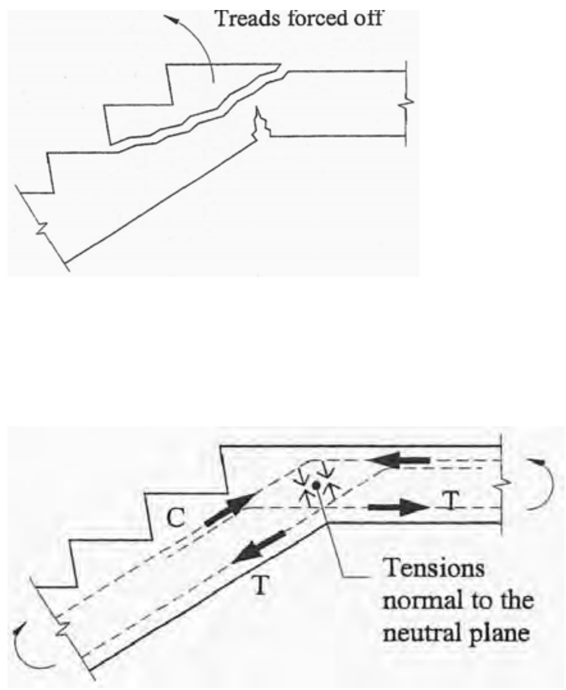
   (a) Relative movement between floors causes the stairs or ramps to compress and can lead to a permanent shortening of the stair. On the reversing cycle of the earthquake displacements, there is insufficient width of support remaining and the stair falls.

   (b) Should a stair or ramp, which is straight (not the scissor stair described below), have a mid-height landing, then it is possible for the front part of the mid-height landing to fail. This was documented in a site accident with a precast concrete stair in the 1980s by Andrews and Butcher (1988) and extensively researched, with recommendations for improved performance, by Simmons and Bull (2000). It is called an "opening knee" failure and is where the top of the landing at the first step is squeezed off as the top of the stair is compressed.

   (c) Due to construction tolerances being used up with either the support landings being built not quite in the correct place or the stairs being manufactured slightly short, there may have been insufficient landing to accommodate even relatively small amounts of interstorey drift.

In Figure 1 describes the issues (a) and (b) above.





C – compression force

T – tension force (resisted by reinforcement)

(a) (b)

Figure 1: Interstorey drift along the stair: (a) compression forces a shortening of the stair and (b) the knee of the stair/landing "opens" and the landing fails.

2) Interstorey drift across the main axis of the stair or ramp:

Relative movement between floors across the main axis of the stair or ramp causes the stair or ramp to be subjected to compression or tension along the main axis of the elements as well as bending and shear due to gravity and bending and shear in the plane of the stair or ramp. The bending and shear in the plane of the stair or ramp occurs because either the stair or ramp is built-in at both ends or if the stair or ramp has a sliding end which is restrained transversely to the main axis (direction of sliding). There is a further case where the stair or ramp is free to move both along and transverse to the main axis of the element. Here, the stair or ramp acts as a cantilever about the fixed end. See Figure 2.

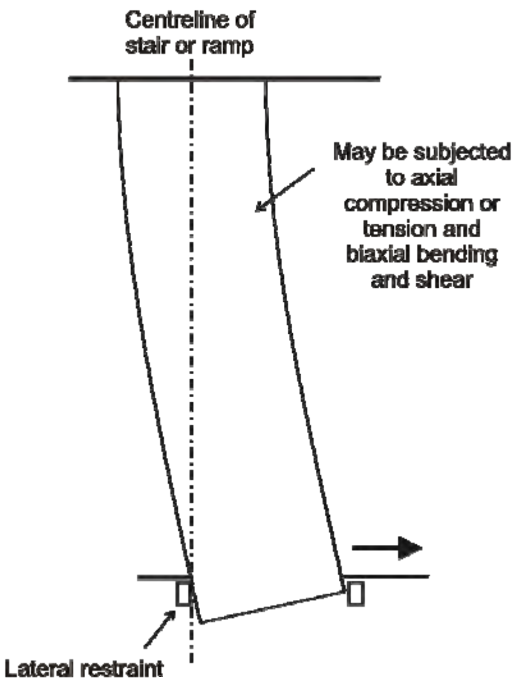


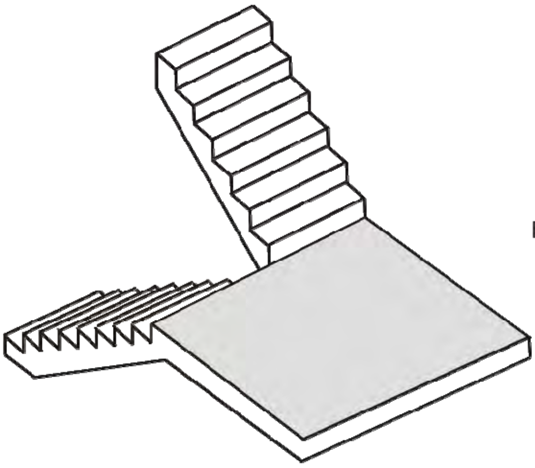
Figure 2: Interstorey drift across the stair or ramp.

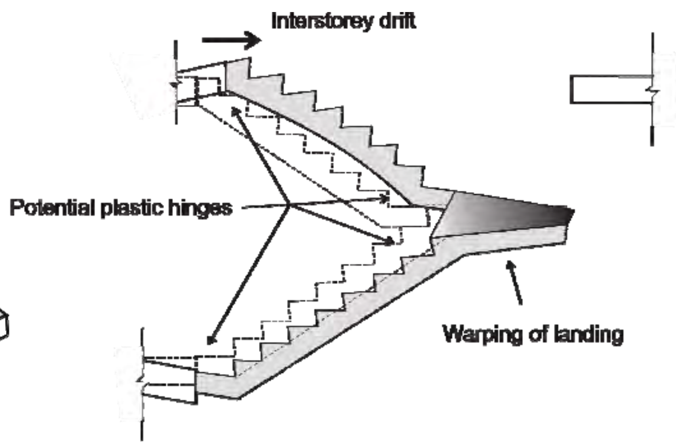
3) Additional Torsion loads:

Twisting along the main longitudinal axis of a stair or ramp introduces additional stresses in to the elements, in conjunction with those loading situations described above. Twisting or torsional displacements occur when:

(a) The supports at each end of the stair or ramp rotate relative to each other. This has been seen in the Christchurch earthquake and elsewhere, where stairs are attached to walls and one end (the wall) is lifted and twisted relative to the other end of the element, as the wall displaces laterally (resulting in either rocking of the wall or a vertical lengthening due to yielding vertical reinforcement in the wall).

(b) “Scissor” stairs: in a stair that has a mid-height landing and the stair turns back on itself (that is not a straight element), interstorey drift between floors can cause overstressing of the stair assembly in a number of locations. Torsion along the longitudinal axis of both flights as well as across the mid-height landing. See: Figure 3 (a) stair layout, (b) distorted stair with plastic hinges and warping of landing.





(a) (b)

Figure 3: Scissor Stairs

3.0 Calculating the required displacements for stairs for buildings

In new buildings, or the retrofit of existing structures, the allowance of inter-storey drift between floors should be calculated using the approach given in current building standards (NBS), but with the modifications noted below.

1. The inter-storey drift calculated for the ultimate limit-state, δ'_{uls}, should be calculated following the steps set out in the Structural Design Actions, Part 5: Earthquake actions – New Zealand, NZS1170.5 (SANZ 2004) and the appropriate materials Standard. The $'$ indicates this values relates to New Buildings Standards. This value should then be multiplied by $1.0/S'_p$, where S'_p is the structural performance factor from the analysis based on New Buildings Standards. This step increases the design inter-storey drift to the predicted **<u>peak</u>** value induced in the earthquake.
2. The drift value found above should be increased by a factor k_{mce}, which scales inter-storey drift found in step 1 to a value consistent with the Maximum Considered Earthquake (MCE) which for most structures corresponds to an earthquake magnitude with a return period of 2,500 years.
3. An allowance should be made for the possible increase in the horizontal span of stairs due to the supports to the stairs being pushed apart by elongation of plastic hinges in beams which span parallel to the horizontal projection of the stairs.

The $1/S_p$ factor for nominally ductile reinforced concrete buildings should be taken as 1.11 for nominally ductile buildings and 1.43 for limited ductile and ductile buildings (NZS3101: 2006, clause 2.6.2.2).

There are a number of reasons why the S_p factor was introduced (EAG 2011, SANZ 2004, 2006, Fenwick and MacRae, 2009). Amongst these is the statement to the effect that the "equal displacement" concept gives an estimate of the peak (acceleration) displacement, which is sustained only once during a design level earthquake. It was considered that damage in a building or building element is the result on a number of inelastic displacements and this could be more realistically represented by a drift that was sustained several times during the design earthquake. On this basis some reduction in the design forces was warranted. This results in the design displacement being S_p times the predicted peak displacement. However, for stairs or other elements that span between adjacent levels in a multi-storey building, it is the peak displacement that may either cause the stairs to be subjected to compression or to be stretched until support is lost and collapses occurs.

To enable egress from an earthquake damaged building it is important that the stairs and access ramps remain in place. To achieve this objective the inter-storey drift found in step 1 is increased by the factor k_{mce}, to give a storey drift appropriate for the maximum considered earthquake. Different factors have been proposed. The earthquake Actions Standard, NZS1170.5 has a factor of 1.8 while a value of 1.5 is used in the Structural Concrete Standard, NZS3101: 2006. The 1.8 value comes from response spectra corresponding to elastic perfectly plastic oscillators. For reinforced concrete members, stiffness degradation occurs when inelastic deformation is induced and strain hardening of reinforcement also increases with inelastic deformation. With these features, the predicted inelastic response is reduced. Furthermore, the additional lateral deformation induced by P-delta actions moving from the ultimate limit state condition to the maximum considered earthquake increases at a slower rate than is implied by the 1.8 factor. Engineers should use which ever k_{mce} factor, 1.8 or 1.5, they are comfortable with.

Tests on numerous plastic hinges in reinforced concrete beams show that the maximum elongation that is generally sustained before failure occurs is of the order of 0.035 times the beam depth, h_b (Fenwick et al 2010). Generally beams in the same bay as the stairs will have two potential plastic hinges; consequently the maximum increase in span between the stair supports due to elongation should not exceed $0.07h_b$.

In assessing the minimum overlap between the stairs and supporting structure, allowance should be made for potential spalling of concrete at the supports from the stairs or supporting structure, say 25mm, construction tolerance, say 20mm, and a residual length to enable the support reaction to be sustained, say 20mm.

Based on the above values the initial support length should accommodate a horizontal extension in the plan direction of the stairs, δ_e, of:

$$\delta_e = \frac{\delta_{uls}}{S_p} k_{mce} + 0.07 h_b + 20 + 25 + 20 \qquad (1)$$

And for shortening in the horizontal direction of the span including residual length of support, δ_s of:

$$\delta_s = \frac{\delta_{uls}}{S_p} k_{mce} + 20 \qquad (2)$$

And for lateral movement of the stairs at right angles to the horizontal direction of the span, δ_l, of:

$$\delta_l = \frac{\delta_{uls}}{S_p} k_{mce} \qquad (3)$$

For example, for stairs where the ultimate limit state inter-storey deflection is 68mm and the depth of beams parallel to the span of the stairs is 800 deep, using the k_{mce} factor of 1.5, the required overlap length of stairs and supporting structure is 221mm, the corresponding allowance for shortening is 120mm and for sideways movement it is 100mm.

For stairs in buildings where structural steel is used the allowance for elongation may be halved for the case where the beams are composite structural steel composite concrete members and it may be neglected where the beams are just structural steel members as in eccentrically braced buildings.

4.0 Retrofit of stairs

Generally in planning to retrofit stairs in a building, it may be simpler to assess the required displacements at the stair supports from the original design calculations rather than carrying out an analysis from scratch to New Building Standards (NBS). With this approach an inter-storey drift associated with the ultimate limit state which is consistent with new Buildings Standards is required. This value can then be used with the equations 1, 2 and 3 given above. However, caution is required as it is necessary to make allowance for many changes that have been introduced in seismic design over the years as our knowledge of seismic behaviour has increased. Hence an inter-storey drift taken from existing calculations, which has been made following previous loadings and material standards, must be modified to allow for the factors listed below:

- The way in which members stiffness were assessed. Note this changes both the calculated magnitudes of inter-storey drifts and the assessed fundamental period of the building;
- The differences in the design response spectra;
- Changes in design methods and changes in strength reduction factors, which were changed for reinforced concrete in 1995;
- The proportion of the peak inter-storey drift that has been taken as the design drift;
- Allowance for the increase in inter-storey drifts associated with P-delta actions;
- The drift modification factor was introduced in Earthquake Actions Standard, NZS1170.5 in 2004. This factor allows for the difference in inter-storey drifts calculated from scaled elastic analyses (equivalent static and modal response spectrum methods) and values found from time history analyses where inelastic deformation was modelled. Similar factors were missing from previous loadings Standards.

<u>Calculation of interstorey drift to the New Buildings Standard having original calculations</u>

There are a number of other changes that have a small influence on calculated deformation but these have been omitted for simplicity and in recognition that the process is approximate.

The inter-storey drift, δ'_{uls}, which in consistent with the New Buildings Standards (NBS) can be assessed from Equation 4, which is given below. Once this value has been obtained the allowance for the required relative movements of the stairs can be assessed from equations 1, 2 and 3.

$$\delta'_{uls} = \delta_{uls} \frac{C(T_1')}{C(T_1)} \frac{\phi'}{\phi} R_s \, P_d \, D_m \qquad (4)$$

Where:

- δ'_{uls} and δ_{uls} are the inter-storey drifts associated with NBS and the initial design calculations respectively;
- $C(T_1')$ is the lateral force coefficient for either the first mode or the equivalent static force for the actions associated with the New Building Standards assuming elastic response and $C(T_1)$ is the corresponding value from the original design calculations;
- $\frac{\phi'}{\phi}$ allows for the change in strength reduction factor and the difference in design calculations based on working stress and ultimate strength methods;
- R_s allows for the change in the way in which section properties are assessed for reinforced concrete members;
- P_d allows for the increase in drift associated with P-delta actions;
- D_m allows for the drift modification factor, which was introduced in NZS1170.5:2006.

The appropriate values of the variable given listed above are given in Table A and the notes below the table.

Table A: Values for coefficients in equation 4

Standard	ϕ'/ϕ	$C(T_1)$	R_s	P_d	D_p	D_m
NZS1170.5 NZS3101:2006	1.0	1.0	1.0	1.0	1.0	1.0
NZS4203: 1992 NZS3101: 1995	1.0	1.0	1.0	1.0 or 1.3*	1.5	Eq. 5**
NZS 4203: 1984 NZS3101: 1982	0.94	4 x C^{α}	1.25	1.3	1.9^{φ}	Eq. 5
NZS4203: 1976 NZS 1900: 1965 or Provisional standard	0.94 1.25 (0.94)	4 x C 4 x C	1.32 1.9	1.3	1.9 - -	Eq. 5
NZS 95, Pt. IV, 1956	1.25	4 x C	1.9	1.3	-	Eq. 5

* use 1.3 if recommended P-delta method in commentary is not used
$^{\varphi}$ NZS4203: 1984 requires the assumed drift to be doubles for stairs. If this factor was included in calculations replace the 1.9 by 0.95.
$^{\alpha}$ The coefficient C corresponds to a displacement ductility of 4 in standards prior to 1992.
** Equation 5 is given below

The drift modification factor is given by Equation 5:

$$\begin{aligned} D_m &= 1.2 && \text{for } h < 15m \\ &= 1.2 + 0.02(h-15) && \text{for } 15 < h < 30 \\ &= 1.5 && \text{for } h > 30 \end{aligned} \qquad \text{Equation 5}$$

5.0 Conclusions

The methods of calculating inter-storey drifts for structural elements, that span between adjacent floors, given in current and previous new Zealand structural design standards has lead to an under-estimate of required displacements that need to be accommodated at supports of stairs and ramps, in major earthquakes. Experience in the Christchurch earthquakes has shown that this has been a major factor in the collapse of a number of stairs and the damage of many others.

References

Andrews, A.L. and Butcher, G.W., (1988), “A Precast Mishap”, Concrete Construction,(NZ), June1988, p3-5.

EAG (2011), Engineering Advisory Group Notes, , “Stairs & Ramps”, Department of Building and Housing, Wellington, 2011.

Fenwick, R.C. and MacRae, G., (2009), “Comparison of New Zealand standards used for seismic design of concrete buildings”, *Bulletin of the New Zealand Society for Earthquake Engineering*, 42(3), 187-203.

Fenwick, R.C., Bull, D.K. and Gardiner, D., (2010) “Assessment of Hollow-core Floors for Seismic Performance”, Research Report 2010-02, Department of Civil and Natural Resource Engineering, University of Canterbury, New Zealand.

Simmons, P. W. and Bull D.K, “*The Safety of Single Storey Straight Stair flights with Mid-height Landings under Simulated Seismic Displacements*”, Research Report 2000-09, Department of Civil Engineering, University of Canterbury, 2000, 293 pp.

SANZ (2004), “Structural Design Actions: Part 5: earthquake actions – New Zealand”, NZS 1170.5: 2004, Standards New Zealand, Wellington.

SANZ (2006), NZS 3101:2006, “Concrete Structures”, Parts 1 and 2, Standards New Zealand, Wellington, New Zealand.