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Development of Typical NZ Ceiling System Seismic Fragilities

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ABSTRACT: Seismic damage to ceilings can cause significant downtime and economic loss in addition to life safety risk. In order to understand this risk and develop mitigation strategies a small project on non-structural damage was recently funded by the FRST Natural Hazards Platform at the University of Canterbury. This particular project concentrates on two ceiling systems which are commonly used, or applicable, in NZ. This paper addresses the development of fragility functions for the ceiling systems based on component fragilities which are obtained from experimental testing of Armstrong$^{(TM)}$ ceiling components. The ceiling system fragility is obtained through Monte-Carlo analysis using in-plane finite element analysis. Demand parameters include absolute acceleration and displacement. The effect of rigid and flexible sprinklers is also investigated. The acceleration resistance is found to be dependent on the ceiling size. This information is being used directly to estimate both ceiling damage and its contribution to overall building loss.

1 INTRODUCTION

The past several decades have witnessed a series of costly and damaging earthquakes. In order to be prepared for such natural disasters, it becomes essential to reasonably estimate, predict and mitigate the risks associated with these potential losses. The figure below gives a representation of how an earthquake may affect a structure. Movement at a fault creates ground motion within the surrounding rock. This motion travels, as waves, to the site of the structure. These waves induce movement in the subsoil. Under large enough excitation all structures will undergo damage. As a result of the ensuing damage, decisions are based on the available information to minimise the effect of losses.

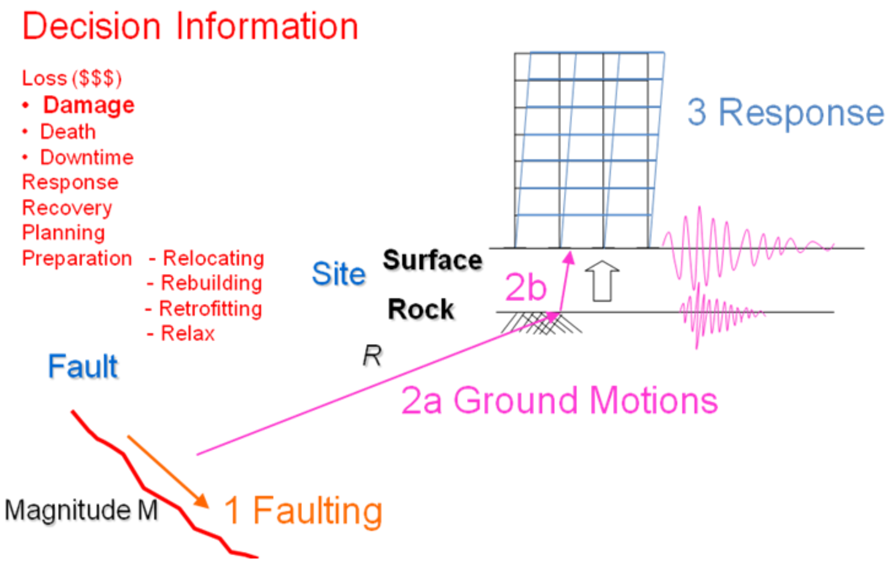

Figure 1. Seismic loss evaluation and decision making process (MacRae, 2006)

Extensive research has been carried out in the past on the seismic performance of structural elements including beams, columns, frames and floors. Although this is clearly important, in many cases for life safety, significant loss can result from the seismic effects on non-structural components of major structures, a relatively untouched area of research.

Damage sustained to non-structural elements can often make up a substantial portion of the overall building losses. These losses, in terms of damage, death and downtime, can be measured in dollar terms (at least by the insurance industry). Non-structural damage includes damage to all contents, partition walls, ceilings and other components of the building, and can be caused by drift, acceleration and displacement. Of particular interest, for this project, is damage to ceilings and suspended ceiling systems as this can not only be expensive but very destructive to contents and dangerous for people in the building. Some ceilings, particularly suspended systems, demonstrate an intermediate degree of attachment to the structure meaning that they can be sensitive to drift, acceleration and displacement actions.

Ceiling damage can occur in a variety of forms such as:

- Fallout (beam elongation causes loss of connection around edges)
- Crushing or buckling (compressive demand through panels)
- Ripping of tiles or panels around sprinkler heads/ break off
- Interaction with HVAC systems or duckworks
- Combinations of these and other interactions

Bradley (2009) showed that for a 10 storey reinforced concrete office building, ceiling damage makes up 14 percent of the total damage costs. While research has been carried out on suspended ceilings most of it has concentrated on testing of full suspended ceiling systems rather than ceiling system members. Additionally, existing research has not addressed methods for analysing ceiling systems. As a result, there is no robust documentation showing the level of earthquake under which no damage is expected for a range of commonly used ceiling systems or a method for analysis of different suspended ceiling configurations.

The aim of the research are:

1. Evaluate capacities of Armstrong(TM) ceiling components under different actions.
2. Develop a methodology for evaluation of ceiling fragility.
3. Assess the effect of sprinkler on ceiling fragility.

2 TYPICAL SUSPENDED CEILING SYSTEM CONSTRUCTION

USG$^{(TM)}$ and Armstrong$^{(TM)}$ are two large manufacturers of suspended ceiling systems. Both of these manufacturers have carried out large scale testing on their products. This has led to the development of seismic resistant suspended ceiling systems and the publication of guidelines specific to their products.

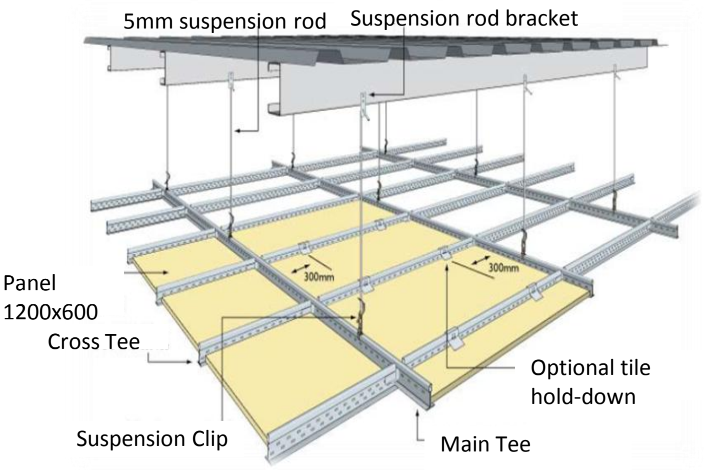

Figure 2.Typical ceiling configuration (based on Rondo, 2009)

However, these tests conducted by the manufacturers and the results obtained have not been published. In this paper, the results for the Armstrong$^{(TM)}$ Prelude ceiling system are shown, and they are called TYPE 1.

3 TESTS

A series of tests devised to verify the strength of typical suspended ceiling components are described. They involve establishment of in-plane tension and compression capabilities of various section types, shapes and sizes. The availability of simple and reliable testing techniques suitable for seismic qualification of ceiling elements is likely to promote their continued and expanded use in buildings and industrial structures; potentially leading to less seismic damage than has been experienced in the past. Since analytical methods are generally not applicable to study suspended ceiling systems and data collected during past earthquakes are not suitable for fragility characterization, experimental methods represent the best and most reliable technique to obtain fragility curves for suspended ceiling systems. Hence, in this project it is decided to test different types of members and connections of a suspended Armstrong$^{(TM)}$ ceiling system under monotonic loading. Table 1 presents a summary of all component tests conducted in this study. As can be seen in the table, each test is repeated 10 times so that the results could be statistically interpreted. From the tests, information on ceiling component strengths are gained, which are used to produce fragility curves for individual ceiling elements for various failure modes in terms of displacement/force.

Table 1. Summary of Component Tests.

N°	Components	N° Tension	N°Compression	N° Shear
1	Main Beam Members	10	10	
2	Cross Tee Members	10	10	
3	Wall Angle Members	10	10	
4	Hanger wide Members	10		
5	Hanging Connections	10		
6	Main Beam Splices	10	10	
7	Cross Tee Connection	10	10	10
8	Main Beam to Wall Angle	40		
9	Wall Angle to Wall	10		

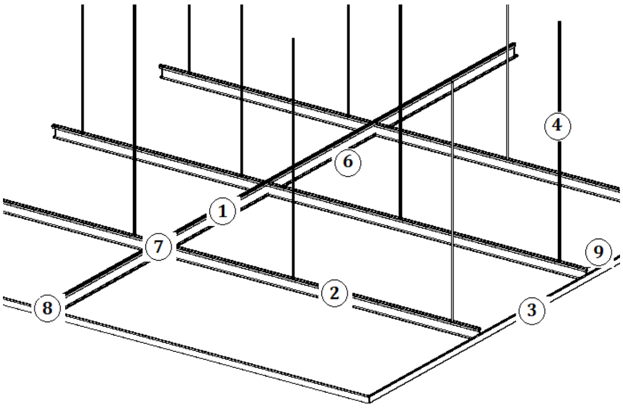

Figure 3: Schematic ceiling with the parts tested.

For the purposes of tests, effort was made to use standard methods but a code with test procedures for all type of components is not available. The tensile tests for the members are standardized by AS/2785. However there is no standard suggesting methods to test the connections, which are likely to be the weakest part of the ceiling system. Also for compression, there is no specific test Standard, and the design of the experiment is very important because the results could be very different with a different configuration. Hence, a rig was constructed which not only maintains the joint position during the test, but also allows for the compressive action to take place without restraining the system too greatly, as this would potentially give higher values. Typical failure modes observed in the tension (member and connection) and compression tests are shown in Figures 4-6.

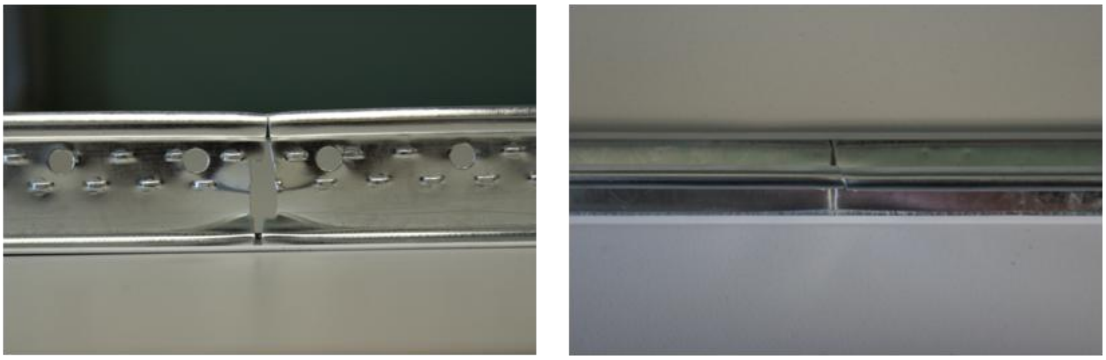

Figure 4. Member failure mode in tensile tests.

Figure 5. Failure mode of connection in the tensile test (left); Failure mode of the riveted connection (right).

Figure 6. Failure mode in a compression connection specimen

During an earthquake the ceiling moves and the rivet connecting the grid to the wall angle is stressed. Due to this it is possible that the acceleration fractures the rivet, as shown in Figure 7, leading to collapse of tiles. The breaking of connections can cause the downfall of many tiles, as witnessed in the library at the University of Canterbury during the September 4 Darfield earthquake.

Figure 7. Failure mode in the rivet connection between the main beam and the wall angle

The lognormal distribution “median, $\hat{x}$” and “dispersion σ (ln x_i)” are reasonable measures to describe failure rather than the “average” and “standard deviation”. Hence, results of the 10 tests were used to calculate the median and dispersion, which were used to obtain cumulative distribution function for the components, to be used in the analysis to follow. For instance, Figure 8 shows the fragility curves for the tension failure of the main beam and the cross tee based on the results if the tension tests. As can be seen in the figure, the median tensile capacity (i.e. 50% of the probability of failure) is 8.5 kN for the cross-tee and 9.4 kN for the Main Beam. Similarly, for all the tests it’s possible to plot a fragility curve like this.

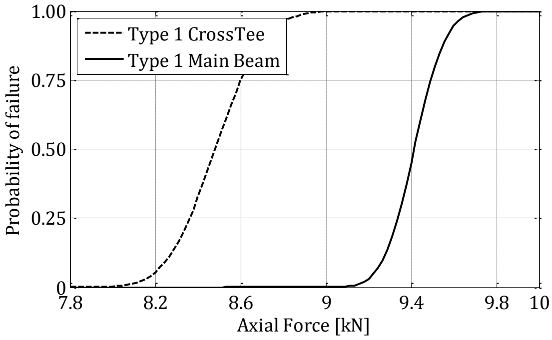

Figure 8. Member fragility curves obtained from the tensile tests

4 ANALYSIS

The development of fragility curves generally involves the use of both mathematical modeling and physical observations. The likelihood of a ceiling failure can be probabilistically obtained if analyses are conducted using a suite of floor acceleration records. However, this is too complex for most designers. Also, it would be difficult to know if an error had been made in the analyses. For this reason, a different method is used in this study.

In parallel with laboratory tests, a Monte Carlo analysis is carried out to derive fragility curves for each component of the ceiling system. Monte-Carlo Simulation involves “sampling at random” to simulate a large number of experiments in order to statistically interpret the result.

The ceiling system is modelled as a two-dimensional grid subjected to monotonic loads to represent the effect of in-plane ceiling acceleration. A finite element analysis program, Ruamoko, is used to carry out the modelling and analysis of the grid. The forces in the ceiling component are calculated and compared with the capacities determined by testing. This allows the critical elements in different ceiling configurations to be identified. Monte-Carlo analysis is carried out on each case study ceiling using the strength distribution of the individual components and varying the applied loads. This analysis provides a spread of strengths for each ceiling, which provides the basis of fragility curves. In this study, fragility curves are prepared for Armstrong(TM) ceiling system by plotting the probability of reaching or exceeding a limit state versus the corresponding median intensity measure.

The main steps of this analysis are:

a) Choose a typical ceiling configuration;

b) Obtain fragility curves for each component and connections by the tests;

c) Perform a structural analysis for a specific value of intensity measure IM;

d) Compute the force in all elements and connections;

e) Generate a Monte Carlo analysis of strengths in all components;

f) Compare strength and demand for each components to see if any members fail;

g) Repeat step e) many times to obtain the probability of failure for that IM;

h) Repeat steps from d) to g) with different levels of IM to obtain a CDF, or ceiling fragility curve for failure.

Figure 9 shows a typical load path for this type of ceiling installation and the components/connection of this load path. Movement normal to the direction shown will be resisted in a similar manner to that shown. Thin green arrows represent induced load from the drop in panels. These are actually applied to the cross beams beside the joints. The thick red arrows indicate load paths through the suspended ceiling members. The shear in the member perpendicular to the load is also considered. When sprinklers are present within some of the panels; the load path differs in the sense that the sprinklers will induce additional restraints once the gap between the sprinkler and the panel closes. In Ruaumoko, beam elements were used for modelling the cross tee and the main beam. The properties (i.e. Young's Modulus, Shear Modulus) of these elements were assumed based on the material characteristics and the dimensions, area and moment of inertia were found by measurement and calculation. To model the sprinkler contact elements were used, which takes into account the gap between the tile and the sprinkler. The stiffness of the contact elements is the same as that of the sprinkler perpendicular to the ceiling.

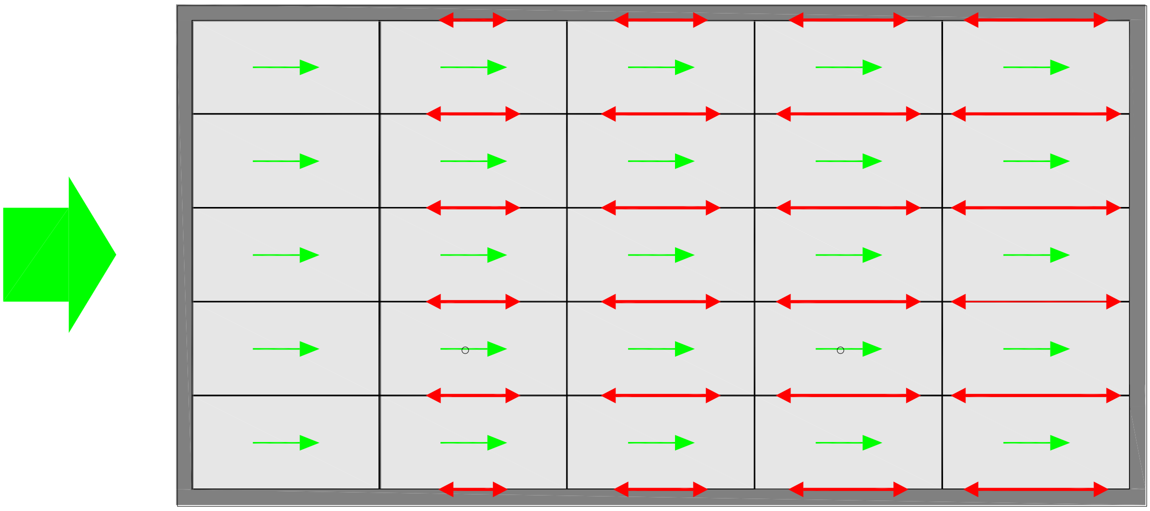

Figure 9. Model used to represent the ceiling

As explained previously, finite element analyses were conducted on a typical NZ ceiling system without and with sprinklers (with different gaps varying between 0 to 20mm). Comparing the resulting member/connection forces to their strengths as randomly picked through a Monte Carlo process allows evaluation as a member or connection will fail for that case. Repeating this for a large number of Monte Carlo simulations gives a probability of failure of the ceiling system. Fragility curves derived through this process for three different ceiling sizes (without any sprinkler) are shown in Fig 10a. As expected, the bigger ceilings are more fragile; because the induced forces in members next to the restrained end increase with increasing number of panels whereas the strength remains the same; thereby resulting in a higher likelihood of failure. The effect of a rigid sprinkler on the ceiling of fragility is expressed through fragility functions (in terms of floor displacement as the intensity measure) in Fig 10b. As can be seen, the gaps between a rigid sprinkler and the ceiling panel shifts the fragility curves by the amount of the gap. It is shown that rigid sprinklers without sufficient gap cause poor ceiling performance. The effect of sprinkler flexibility is not investigated here, but it is obvious that a reasonably flexible sprinkler does not induce noticeable additional restraints to the ceiling system; and hence the fragility function of such ceilings is the same as that of the ceiling without any sprinkler.

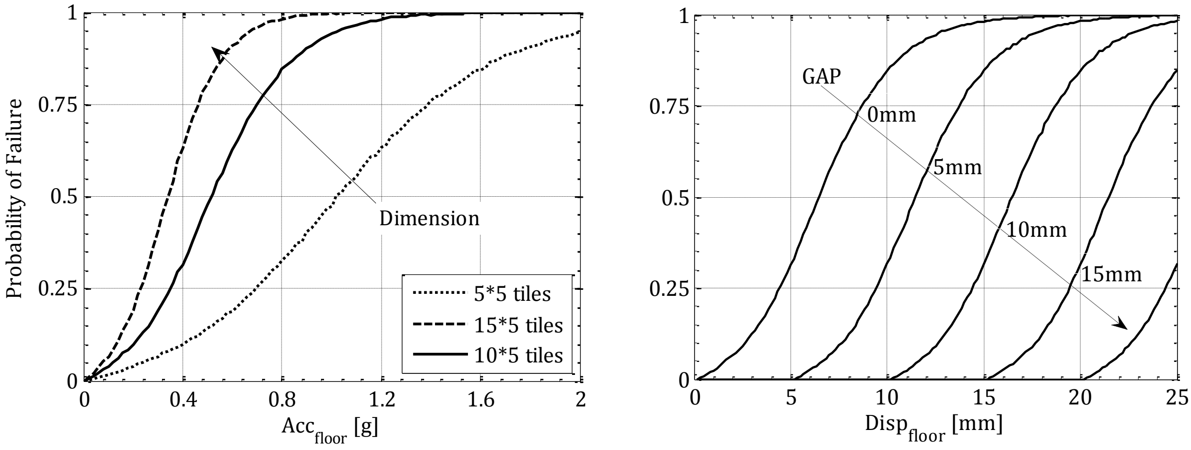

Figure 10. Fragility curves (i) (with the floor acceleration as IM) for different ceiling size (Left); (ii) (with the displacement as IM) for different gap between the sprinkler and the panel (Right).

5 CONCLUSION

Tests were conducted and analyses were undertaken to obtain elements and ceiling seismic fragilities for the Armstrong$^{(TM)}$ Prelude ceiling system. In particular, it was shown that:

1. The most critical ceiling element was the compression connection at the ceiling boundary.
2. A methodology for developing seismic fragility was developed. It was shown that the median floor acceleration that caused ceiling failure was around 1g for a ceiling of dimension 5*10 tiles (6x12 m). This failure acceleration decreases with an increase in ceiling size.
3. The presence of stiff sprinklers made other elements critical and significantly reduced the floor acceleration required to cause failure.

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