# SUSPENDED CEILINGS : THE SEISMIC HAZARD AND DAMAGE PROBLEM AND SOME PRACTICAL SOLUTIONS

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SYNOPSIS

Traditional ceilings in rigis buildings generally caused few problems when under earthquake attack. The introduction of modern suspended ceilings with light metal grids and lay-in tiles or light fittings has created an entirely new situation. Increased flexibility of modern buildings has added to the problem, particularly with respect to the integration of ceilings and partitions.

The authors discuss the theoretical considerations of the problem and relate these to evidence from earthquake damage. Code requirements are reviewed and a number of typical solutions are presented.

Economics are briefly discussed and in conclusion the authors refer to a number of aspects not fully understood at present. Suggestions are made for further study and testing to clarify some dynamic aspects and fire barrier problems.

## 1. INTRODUCTION

The significant progress made in recent years towards ensuring that structures will survive an intense earthquake allows, and indeed demands that a greater effort be directed to finding solutions for the avoidance of non-structural damage. This form of damage typically results in the greatest monetary losses and additionally leads to significant risk to life and limb of people in and around the affected building.

The general aspects of non-structural damage have been discussed elsewhere(1), (2), (3), but the particular problem of ceiling damage has so far not specifically and in adequate detail been dealt with in the literature. The action of ceilings in Earthquakes is much more complex than might appear on superficial consideration and the development of details that are effective, practical and economical requires considerable thought and ingenuity.

Although there was evidence for some 15 years that existing ceiling systems presented a hazard, the expense involved in modifying these and developing new types, retarded progress. Gradually however, initially because of requirements for Government financed buildings and later those in NZS 4203 : 1976(4), improved systems became available.

## 2. EVIDENCE OF HAZARD FROM EARTHQUAKE DAMAGE

Because traditional structures usually were low and had many walls they were much stiffer than modern buildings and the problem of hazards due to ceilings was not evident prior to about 1964. If a traditional building survived an earthquake, so did its ceilings. In any case while survival of the structure was the principal and barely achievable objective, reduction of life hazards due to ceilings and partitions was obviously a goal of a lower order of priority. Additionally in older buildings ceiling and partitions were built insitu, with all components well fastened together and damage to ceilings, except in buildings near collapse, consisted usually of cracking only. Thus, excepting for a few isolated cases, real problems did not arise until the advent of modern suspended ceilings, with their inlaid lighting panels and integrated removable partitions. The problem was further aggravated by the flexibility of newer structures designed to meet the requirements of the architectural style of the last 15 years.

In 1966, as a result of the Gisborne earthquake(5) (MM7), a heavy suspended gypsum tile ceiling fell through a height of two storeys into the public space of a bank building. This space was fortunately vacant at the time and no casualties resulted, but the event alerted designers in New Zealand to the hazard. Although this earthquake had a recorded maximum ground acceleration of 0.3 g, judging from the lack of damage to the many parapets which had been completely shattered in earlier earthquakes - the ground and building velocities associated with the three to four strong pulses, could not have been very large. Nevertheless the dynamic response of the ceiling was sufficient for the supports of the tiles to spread and allow the tiles to drop. (Figs. 1, 2, 6). The building itself was undamaged.

Prior to this earthquake, some ceiling damage was also reported from the 1964 Anchorage, Alaska earthquake, but most of this occurred in severely damaged buildings. Failure seemed to be due to stresses induced by building deformations e.g., at the West Anchorage High School. The more important lesson from this earthquake was that suspended lighting fixtures needed to be better secured so as not to rely on the electric wiring for survival (fig. 5).

Ceiling damage similar to that experienced at Gisborne occurred at Westport in a region of MM8 during the 1968 Inangahua earthquake.

The most extensive damage to ceilings and partitions occurred during the Managua earthquake of 1972 (fig. 4). Of particular significance

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was that this damage occurred in a structure reported as structurally only moderately damaged. The importance of this event, which caused non-structural damage reported to have amounted to 80% of the total value of the building and its contents, was that it finally seemed to have convinced architects and clients that something needed to be done. The above figure for losses did not include those resulting from the disruption of the function of the building.

Reference to other damage is made elsewhere in the paper.

## 3. DEVELOPMENT OF SEISMIC CEILINGS

### 3.1 Historical

Suspended ceilings came into increasing use in New Zealand 15 years ago to provide a rapid means of erecting a ceiling to meet a wide range of architectural and services requirements. Primarily these requirements were aimed at obtaining varying surface texture to the ceiling, varying acoustic properties, support for lighting and service fittings, and a ceiling support system which did not interfere unduly with the services in the ceiling space. Loading requirements were gravity only, and vertical stiffness for appearance was the major concern. Horizontal stability was obtained by fixing the ceiling in its own plane to the confining walls or partitions. To cater for seismic areas a minimum level of resistance against moderate earthquakes was provided in the form of diagonal wire bracing in the ceiling space, fixed at intervals over the ceiling plane and to the building structure above. The identification of potential damage and collapse mechanisms generated by moderate seismic excitation in these early ceilings is ciscussed in sections 3.5 and 3.6. In the last few years New Zealand suspended ceiling manufacturers and erectors have upgraded the basic grid systems to overcome these design and erection faults, and provide an acceptable level of seismic resistance. A number of these solutions are outlined in section 4.

A third generation of suspended ceilings is now being developed with seismic resistance considered at the conception stage. This approach should lower costs. While the new systems have more efficient members and joints they still are of the metal grid/lay-in tile type and the considerations outlined in this paper apply.

### 3.2 Typical Suspended Grid Forms

The practical application of the early development requirements lead to two forms of construction, both employ light metal grid members with tiles or pan type light fittings laid into the grid. The ceiling grid may also be used to support surface-mounted light fittings, air difusers and various mechanical service fixtures.

Fig. 7 shows the first of the two principal systems. All grid members are in the same plane. Using the terminology of ASTM C635-69 the cross runner Tee-rail members are chipped at their ends through the vertical web of the continuous main runner Tee-rails. This type of system is used generally with light to medium weight tiles (light: Less than 5.6 $kg/m^2$ medium: 5.6 $kg/m^2$ to less than 15.0 $kg/m^2$, heavy: 15.0 $kg/m^2$ and greater).

The second ceiling form, (fig. 8), is built up from main runner Tee-rail members suspended by cold formed steel clips beneath norizontal strong back or carrying channel members running at right angles. Medium to heavy weight tiles are generally used in this grid system with the tiles supported on two opposite sides only. Both ceiling forms are suspended from the building with cold formed steel wire, strip or angle hangers attached to the main runner in the first system and the carrying channel in the second. For special effects, such as a fully concealed grid ceiling, specially formed tile and support splines fitted into the kerfs or adjacent tiles may be used in the above two basic suspended ceiling forms.

### 3.3 Grid Horizontal Support

Provision of resistance to horizontal excitation of large suspended ceilings has generally been aimed at by means of diagonal wire bracing to the floor above. This method is specified in a UBC draft (refer section 5) and was the subject of limited dynamic testing[11]. While such resistance, on the assumption that the ceiling is stiff in a horizontal plane, is not too difficult to provide, the true dynamic action of a wire braced ceiling is very complex. (See section 3.6).

The second method of providing horizontal resistance has been by fixing the ends of grid members to partitions or walls. However this method is acceptable only where free movement between intersecting partitions is not required and where they can cope with the imposed loadings. This is not the case where ceilings are heavy and large.

### 3.4 Materials

The two materials used, almost exclusively, in fabricating the ceiling grids are extruded aluminium alloy to ASTM B221-76a, Alloy 6063, temper T5 and cold-formed galvanised steel to BS 1449. Tee-rails and wall mouldings are formed from the aluminium alloy whereas the cold-formed steel is used for Tee-rails, wall mouldings, carrying channels, hangers and braces.

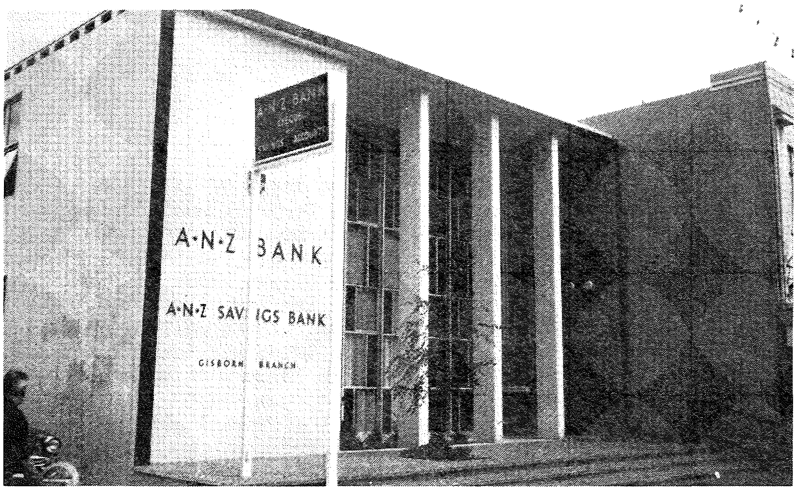
### 3.5 General Discussion of Seismic Effects

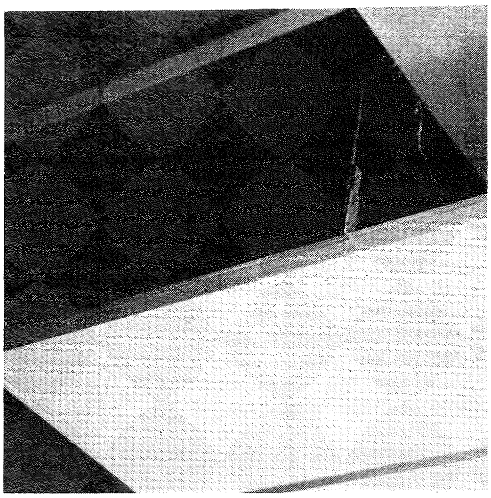
Seismic effects (and also strong differential wind pressures) create problems that were not adequately catered for in traditional systems. Hazardous ceiling damage may be the result of the dynamic response of the ceiling system or it may be due to stresses induced by the deformation of the building and/or partitions.

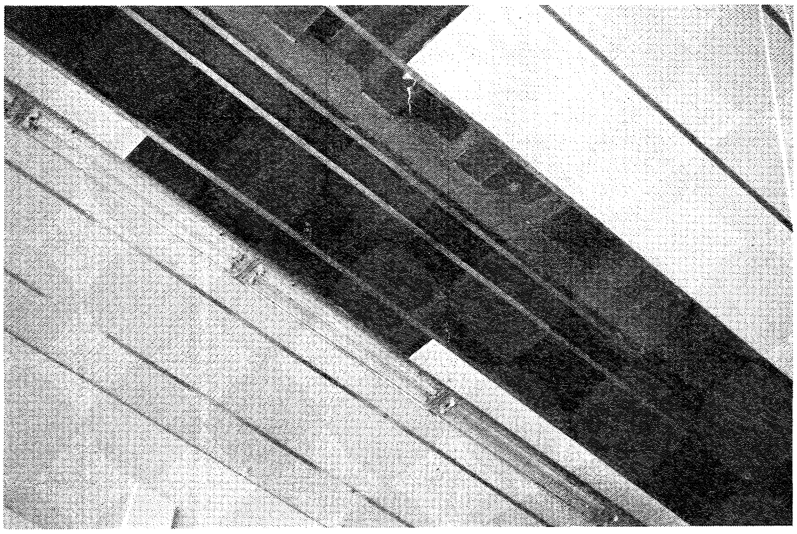
The motions causing excitation of the ceiling are those transmitted by the supporting floor above. Having been modified by the building they are much more deterministic than the original ground motions[7] and strongly dominated by the building periods. Nevertheless strong response will occur at other periods and making the ceiling support system rigid is a safer approach than any attempt to dynamically uncouple the ceiling. Uncoupling also requires in general very long hangers which creates practical difficulties.

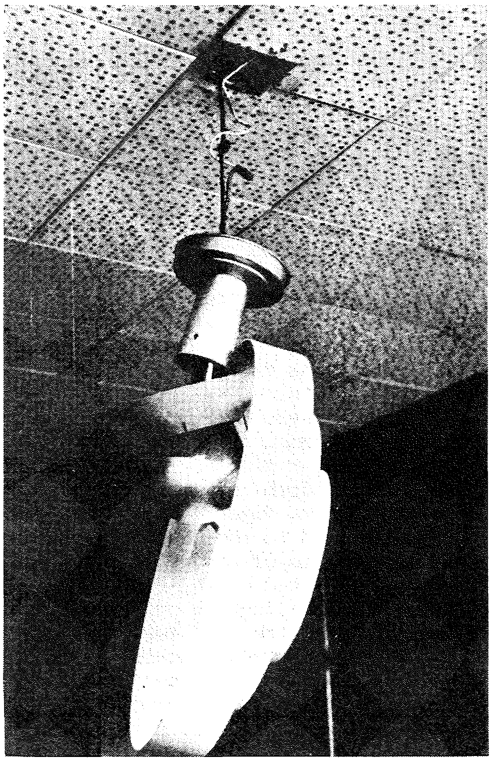
Input motions both horizontal and vertical are potentially capable of causing a vertical response of ceilings and in large ceilings wavelike motions may develop causing instability problems.

Additionally to the dynamic response, ceil-







**Figs 1-6**
**(Top LH. Counterclockwise)**

**Figs 1,2,6**
**Gisborne Eq 1966**

**Fig 3**
**Emergency Entrance. Olive View Hospital, San Fernando Eq 1971.**

**Fig 4**
**Banco Central, Managua Eq 1972.**

**Fig 5**
**Anchorage Eq 1964**

ings are subject to special interaction between themselves, structure and partitions.

The nature of building deformations in severe earthquakes affecting non-structural elements have been discussed elsewhere(1), (2). With ceiling - partition systems, the designer must ensure that the system accepted for a particular job can accommodate the deformations estimated to take place at the level of earthquake intensity specified or selected for checking serviceability and safety.

Competent design requires that consideration be given to these aspects when deciding at the sketch plans stage on the required minimum stiffness of the structural system. Buildings designed to the maximum allowed flexibility of the N.Z. code i.e. 0.5% of the storey height under code loading (17.5 mm for a 3.5 m storey height), are likely to lead to difficult detailing for ceiling and partitions. This becomes evident when realistic deformations are obtained using the appropriate modifiers to account for inelastic building response.

3.6 Potential Damage Areas

To ascertain likely areas of weaknesses in traditional suspended ceiling systems, criteria of relative mass, stiffness (both material and configuration), damping, strength and toughness, as well as interface conditions will be considered as the seismic generated loads are followed through the ceiling and partition load paths.

Consider the ceiling form shown in fig. 7 where the main runners and cross runners are in the same plane and bracing is fixed to runners at points over the ceiling plane. Loads generated in the ceiling plane be acceleration of the ceiling mass are transferred horizontally at right angles to the direction of the laoding to lines of lateral support. These lateral support lines are the lines of main runners or lines of cross runners on which the bracing is fixed. Load transfer is initially by horizontal bending in the grid member until the lay-in tiles bear against the grid at diagonally opposite corners. (fig. 9). Tiles are then put into inplane shear and the grid members into transverse shear across the joints. This is the main load carrying mechanism due to its high stiffness relative to bending of the runners. With components of horizontal loading at right angles to the cross runner, the initial grid deflection may well be by rotation of the cross runner clip joint until the tiles bear on the grid members. Hence even less load resistance is provided by the grid members. Provided the bracing points are not spaced too far apart, say as recommended by the draft UBC Standard, tile materials in common use have sufficient strength to carry the inplane shear loads. Although the tiles may be the actual load carrying mechanism, the grid should have sufficient capacity to carry the ceiling load without the lay-in tiles as they may in some areas be replaced by lay-in pan light fittings etc. which do not have the inplane stiffness of the tiles. Also, the case where tiles may become dislodged by vertical motion of the ceiling during a seismic event.

Tests have confirmed that cross runners adjacent to the bracing point are particularly susceptible to damage as under cyclic loading, compression tends to buckle the clip joint. The effect is a shortening of the member so that when the loading is reversed it tends to carry a higher share of the tension load. This may cause the joint to fail.

This type of damage mechanism may be accentuated where a number of braces are fixed along the length of a runner and the braces have a relatively wide range of stiffness. Under seismic loading the runner will endeavour to distribute the horizontal load to the braces relative to their stiffnesses unless the runner or its connections deform sufficiently to materially alter the distribution pattern. The wider the range of bracing stiffness, the greater will be the demand on the strength of the stiffest brace and on the toughness of the runner connecting the braces.

This suggests that poorly fixed and weak braces can lead to progressive collapse of the horizontal restraint. Wire bracing is particularly susceptible as the fixers prefer the brace to be slack so that the ceiling is pulled up out of plane and the tightness to which the wire is twisted at its end connection can vary between braces.

Wire bracing, or more generally tension only bracing, can only carry horizontal load if sufficient ceiling gravity load can be picked up from the hangers to balance the vertical component of the brace load (fig. 10).

In the case of diagonal braces lying at $45^{o}$ to the ceiling plane, a biaxial loading from an acceleration of .7 g requires the braces to carry the total ceiling dead load. However, the ability of the grid system to transfer dead load from the hangers to the bracing points is dependent on the runner vertical strength and stiffness, thus the ceiling must swing up about the point of brace attachment to the building to develop this load transfer. In systems where braces are able to take compression, swinging may still take place depending on horizontal stiffness of the system.

Swinging motion may require wide separation of the ceiling at the perimeter additional to that for interstorey displacement of partitions otherwise the confining walls will be called upon to carry loads they were not designed to carry. Alternatively the ceiling or wall may be damaged by pounding. The swinging action also generates high accelerations in the suspended ceiling when the supporting building commences to move in the opposite direction to that of the ceiling's swing (whiplash action). This motion, which is not necessarily uniform over the ceiling, places an added load on the runner, particularly the cross runner joint. (fig. 11).

A draft UBC Standard (refer Section 5) recommends that at each point of horizontal support in the ceiling plane, four orthogonal braces be provided. In practice due to equipment in the ceiling space conflicting with bracing wires, two braces in each direction have sometimes been displaced from each other along adjacent main or cross runners. (fig. 12). Under biaxial seismic attack the swinging action will require differing vertical balancing load demands on these two horizontal support points potentially placing added vertical racking forces on to the interconnecting runners and joints.

The interface between partitions, and ceiling

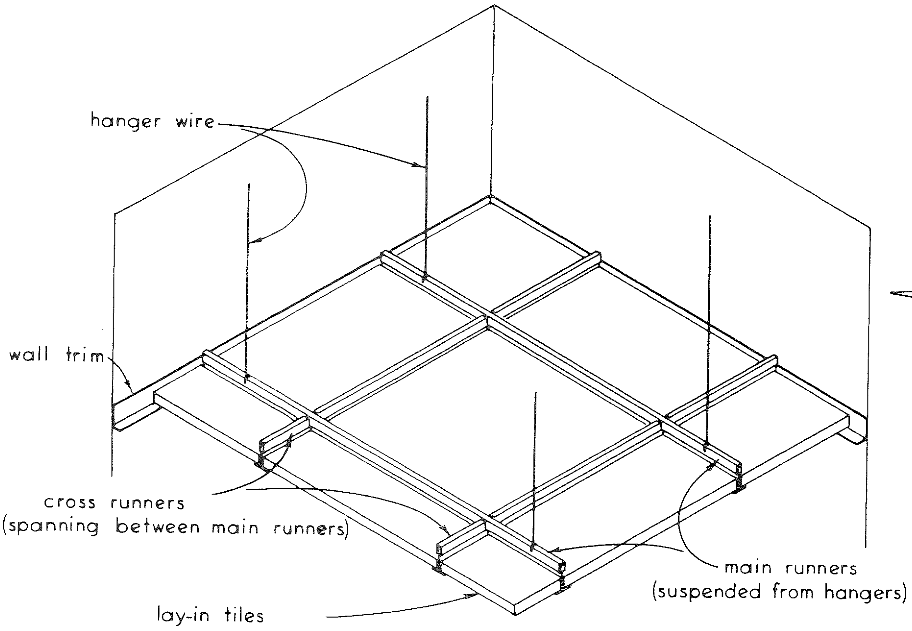



FIG 7
Two-way Inplane Suspended Ceiling Grid System

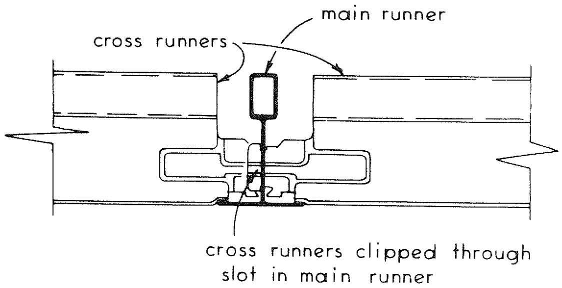



FIG 7A
Cross Runner Joint

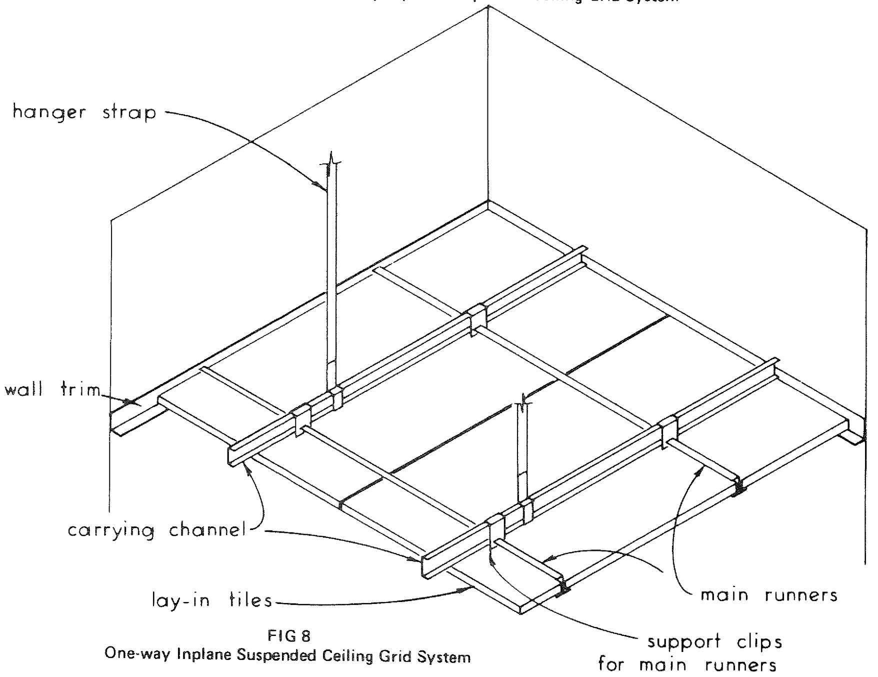



FIG 8
One-way Inplane Suspended Ceiling Grid System

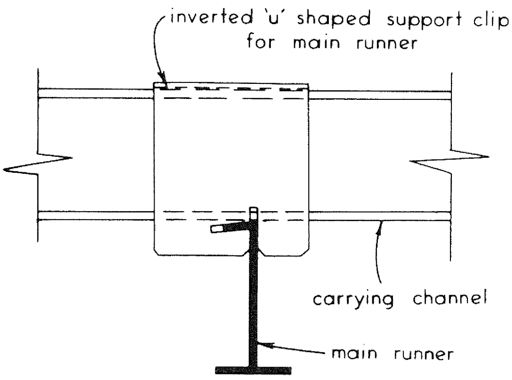



FIG 8A
Main Runner
Support Clip

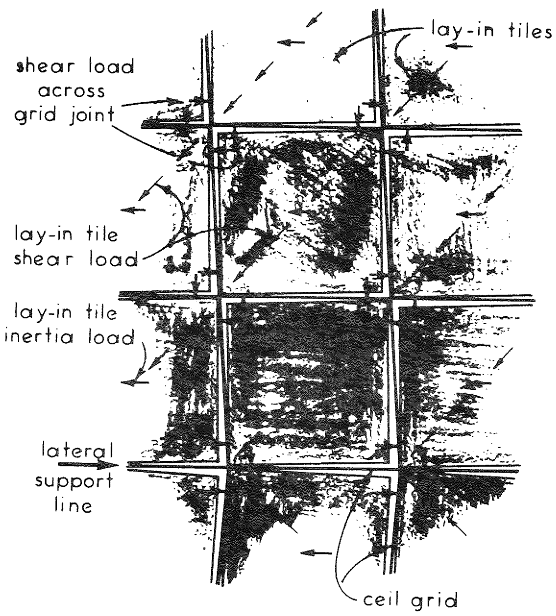



FIG 9
Load transfer in Plane of ceiling to Lateral Support Line

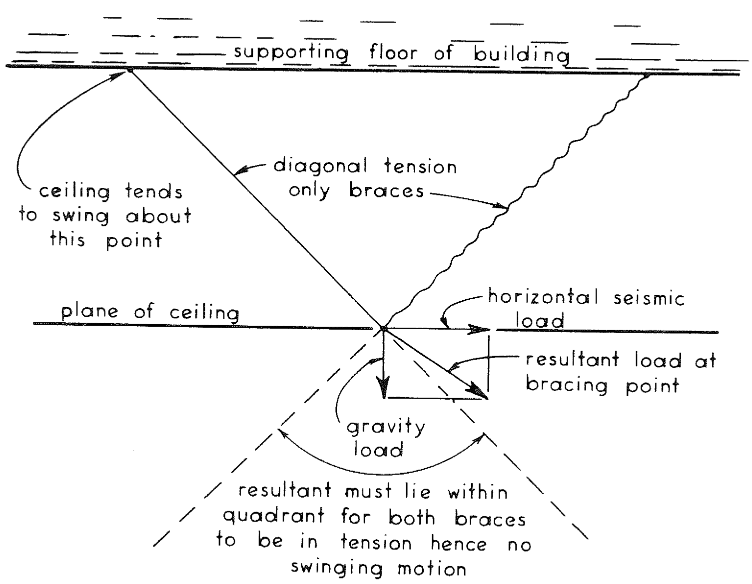



FIG 10
Tension Only Bracing

and partitions has considerable potential for extensive damage. (fig. 13).

Relative to the bottom, the top of partitions can accommodate only small inplane dispacements, but much larger ones perpendicular to their face. Consequently interstorey drift, if not provided for, will cause extensive damage.

Where a wall moulding provides support for edge tiles in an unattached ceiling the potential exists for these tiles to drop out particularly since the last cross runners are not connected to the main runner to take horizontal cantilever loads and hence there is little restraint against spreading.

Where relatively large masses such as light fittings are attached to the ceiling, or fittings with different response characteristics from the ceiling are fixed, potential for damage exists. Meehan and others in reference 12 provide graphic evidence that an intense earthquake, even though lasting only a few seconds can cause pendant hung light fittings to wreak havock. The violent swinging of light fittings applied a torsional rotation to the runners from which they were hung. In the case where the light fittings were fixed to the line of cross runners, this motion tore out the connection into the main runner at either end, allowing light fittings to drop as well as distorting the remaining ceiling grid, thus reducing its ability to carry self weight during the remainder of the seismic event. The effect on main runners, where the light fittings ran parallel, was dramatic as the more positively connected main runner pulled away over its whole length from the cross runners collapsing the immediate area of the ceiling.

Yet another undesirable practice is the fixing of surface mounted light fittings by screwing directly into brittle plaster tiles.

Excepting in the case of very rigid ceilings, passing services e.g. sprinkler head connections through the ceiling will lead to damage.

Grid members must have sufficient stiffness and toughness to avoid differences between intended and actual behaviour leading to damage. In the ceiling shown in fig. 8 the intended loadpath is from ceiling title via main runner clips (fig. 8b) to axial load in the main runners. However where tiles fit closely against each other, the flexibility of the main runners and clips may still allow pounding between ceiling and confining wall.

Earliest forms of ceilings had the main runners directly hung from above without any cross members that would act as spacers. The consequences have been discussed in Section 2 (figs. 1, 2, 6).

## 4. CONSIDERATION IN THE DESIGN AND DETAILING OF COMPONENTS

### 4.1 General

Due to the unpredictable performance of pendulum type suspended ceilings outlined in Section 3.5 all N.Z. proprietary suspended systems have adopted the approach that the ceiling should be rigid and rigidly fixed to the building. Partitions must then be detailed in a manner that will avoid damage due to differential movements while at the same time providing them with any lateral support they require. Clearly ceiling and partition systems must always be considered in conjunction. In common with all design, all members and connections must be capable of withstanding the imposed forces.

### 4.2 Clipping of Lay-In Tiles

The holding down into the ceiling grid of lay-in tiles against net vertically upward acceleration (or differential wind pressure) is a problem that has not been adequately solved due to the difficult but fundamental practical requirement of ready replacement of an individual tile and holding down mechanism following service access to the ceiling space. Positive holding down of the tiles is particularly important where the inplane load transfer mechanism described in Section 3.6 and fig. 9, depends on the tiles. Two basic types of spring clip have been developed by ceiling manufacturers meeting the seismic requirements of reference 13 i.e. replacement should be easily achieved, upward restraint not less than 1/3 the tile weight and replacement must automatically lock the tile into position. A remaining problem is that tiles may be damaged after a number of uses.

The first clipping system is shown in fig. 14 consisting of a 29 swg by 13 mm wide spring steel strip formed into a balloon in vertical section, and pop riveted to the vertical web of the ceiling runner, one clip on each of the two opposite sides of a tile. Vertical restraint to the tile is gener-ated as the tile lifts forcing the balloon spring to deflect horizontally away from the lifting tile. Where an upward force of approximately twice the tile weight is applied the spring deflects sufficiently to allow the tile edge to clear the spring. To replace, the tile is dropped against the spring and pulled down past it by a strip of paper or card placed between the spring and tile edge. Considerable care is required to match the tile shape, balloon shape and position, and spring stiffness to obtain the necessary restraint characteristics. An inplace cost of approximately $0.30 per clip has made the use of this type almost prohibitive.

Fig. 15 shows the second type of clip developed using plastic covered helical curtain wire with an overall diameter of 4 mm. The 300 mm length of wire passes in a loop through two neat holes drilled through the runner vertical web at the level of the tile top surface. The free ends of the wire lie equal distant over the top surface of the two adjacent tiles. Each tile is restrainted by two legs of wire, one on each of two opposite side of the tile. As the tile lifts vertically, restraint is generated by the wire curving sharply upwards. An upward force of just under twice the tile weight is required to completely remove the tile. To replace, the wire is deflected vertically upwards by hand so as to allow the edge of the tile to drop down into the grid and the wire clip to snap back into position across the top of the tile. As with the spring steel strip, considerable care is required to match the position of the spring with the tile used as well as the tile fit into the grid and the spacing of the holes to take the wire loop. However, the inplace cost is considerably less than that for the spring steel strip.

It is to be hoped that with time a simple inexpensive tile restraint mechanism can be devised to ensure the integrity of the ceiling plane for seismic lead transfer and resistant against differential wind pressure.

4.3 Cross Runner Joints

The ceiling form described in Section 3.2 and fig. 7 where the main and cross runners are in the same plane, places considerable reliance on the capacity of the cross runner joint through the main runner to carry axial seismic loads and shear generated by inplane load transfer described in Section 3.6. This is particularly so on lines of lateral support.

To enhance the joint capacity additional proprietory clips have been developed to fit across the joint to hold the two adjacent cross runners together. More recent developments have been aimed at introducing a 'U' shaped clip which passes through the main runner and crimps through the two legs of adjacent cross runners so that they butt tightly into the side of the main runner. Refer fig. 16.

This produces a stiff and relatively strong connection but obviously a higher inplace unit cost which needs to be discounted against the higher load capacity of the joint allowing a higher load to be accumulated in the runner between braces spaced further apart.

4.4 Main Runner/Carrying Channel Clip

The problem of laod transfer to the carrying channel via the clip from the main runner, described in the next to last paragraph of Section 3.6, has to a large extent been overcome by using a main runner section with a high stiffness to horizontal transverse loading, placing the carrying channels closer together and by the development of a stiffer clip resistant to loading at right angles to the main runner. The aim has been to bring the maximum horizontal deflection of the cross runner at the level of the tiles, under code earthquake loading, down to less than the tolerance gap between tiles and their supporting runners.

The major improvement has come from producing a broader horizontal top flange to the main runner and a clip which holds this flange tight against the bottom flange of the carrying channel. This allows a moment couple to form between the flanges in contact which is considerably stiffer than the earlier form shown in fig. 8b. Horizontal shear is carried by either a pop rivet through the carrying channel web and clip, or crimping the side of the clip between the flanges of the carrying channel.

For ease of fitting and adequate performance the clips are required to be punched out to a tolerance of $\pm$ 0.05 mm, this means the forming of the carrying channel needs to be to a similar tolerance.

Fig.17 shows another form of the clip which does not require such close tolerance in manufacture, but does require four pop rivets per clip to be placed with some care as to position to obtain the required stiffness.

4.5 Horizontal Support by Bracing

Three forms of bracing to the ceiling plane are now in general use as shown in fig. 18 which do not rely on the ceiling weight to provide the vertical component of force in the brace when the ceiling is excited horizontally. Where the ceiling space is less than say 1 m high and to provide clearance for extensive services equipment, rolled hollow steel sections have been fixed to the underside of the floor above to act as vertical cantilevers. Since the ability of the members in the ceiling plane to transfer loads is not great, many vertical cantilevers are required, making this solution expensive.

Bracing form A, (fig. 18) is a modification of the four diagonal wire brace discussed in Section 3.6 with the addition of a vertical strut formed from light steel or aluminium tube or steel angle. Figure 19 shows the arrangement with a tubular strut suggested by Meehan[14].

In general bracing form B is the preferred arrangement with the braces cut from cold formed angle in the 20 x 20 x 1.22 to 50 x 50 x 4.8 range depending on ceiling seismic load to be carried and height of ceiling space. This bracing form is the most economic and versatile for catering with varying ceiling forms, congestion in the ceiling space and verying height of ceiling space. With the compressive capacity of the two diagonal bracing members a relatively stiff brace is produced as well as providing a vertical restraint to wave motion in the ceiling plane. Bracing form C is used where the hangers have a compressive capacity and the ceiling space is congested with services. They are placed in opposite handed pairs down the length of a bracing line.

4.6 Horizontal Support by Fixing the Ceiling Grid Members at the Perimeter

An adequate form of horizontal support to the ceiling can be provided by fixing, in the ceiling plane, the ends of grid members to a member, e.g. a floor beam sufficient in capacity to take the seismic loads from the ceiling.

Where the horizontal support is provided by walls or partitions e.g. at corridors, the design must ensure that no relative movement between them can occur.

The strength and variation in strength of the runner joints will determine, for a given ceiling the maximum length of runner between points of restraint. Upward buckling restraint should also be provided to the ceiling grid members, as generally the tiles will provide sufficient horizontal restraint and vertical downward restraint is supplied by the hangers.

4.7 Ceiling Perimeter Separation

In the case of flexible buildings separation between ceiling and walls or partitions is generally required to avoid damage caused by interstorey drift.

Separation between ceiling and walls may also be required in more rigid buildings if the ceiling is designed to transfer horizontal loads via inclined braces to the floor above rather than to the walls. This will usually be the case with larger ceilings.

Where drift is not a problem, and the ceiling

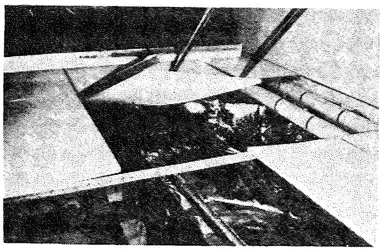


FIG 11
Failure of Cross Runner Joints

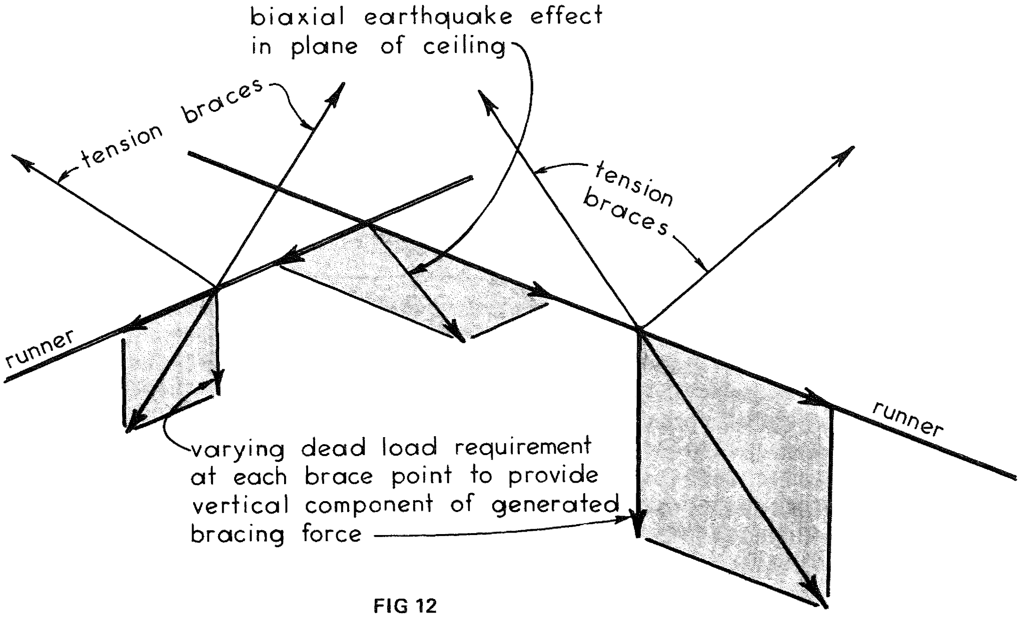



FIG 12
Effect of Separating Bracing when Loading in Orthogonal Direction

FIG 13
Damage at Ceiling Perimeter

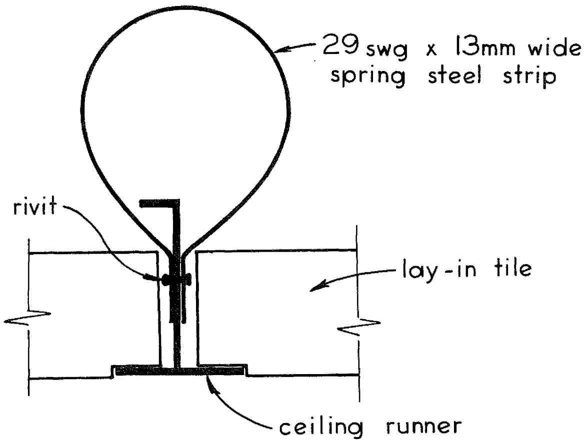



FIG 14
Balloon Spring Tile Clip

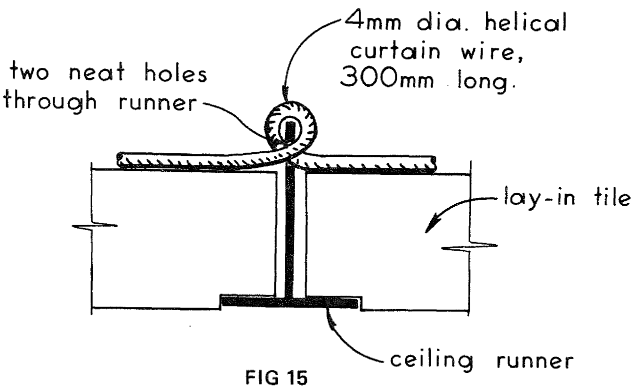



FIG 15
Curtain Wire Spring Tile Clip

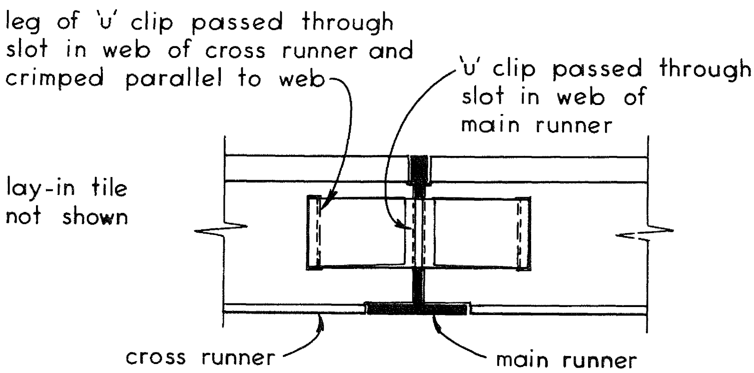



FIG 16
Clipping of Cross Runner through Main Runner

grid less than about 2 m below the supporting floor, a 5 mm separation is generally adequate.

A satisfactory way of providing this separation, as well as tying the ends of cross runners and main runners, is to introduce a runner around the perimeter of the cei ng fixed to the runners at right angles and separated the required distance from the wall. The danger of loss of support for the perimeter tiles is thus avoided. The perimeter runner is preferably supported vertically by hangers from the structure above, or alternatively by the end of a carrying channel. An angle moulding may be fixed to the wall to hide the perimeter runner and provide at the same time a means of fire stopping the ceiling without destroying the ability of the ceiling to move horizontally. (fig. 20).

An alternative solution that will deal with moderate movements is used in a proprietary system to support the free end of runners at the perimeter of the ceiling but still allow the ceiling to deflect horizontally. A spring clip holds the top flange of the cross runner thus allowing axial movement of the runner. A wide vertical extension of the clip fits behind the wall trim, allowing controlled horizontal movement of the runner parallel to the wall.

One of the most damaging actions on ceilings is due to the effects of interstorey drifts at the interface between partitions and ceilings when movement is parallel to the plane of the partition. Tests have shown that timber frame partitions lined with plaster boards or wood based products can sustain shear deformations of 0.6% without damage. The problem is that the ceiling connection or ceiling system are insufficiently strong to deflect the partition, thus resulting in damage to the ceiling or connection.

To overcome the problem, a longitudinal sliding joint is introduced which at the same time retains lateral support for face loads on the partition. (fig. 21). More complex is the provision that must be made to overcome the incompatibility at the right angle junction between partitions. Provided drifts are not too large the detail shown in fig. 22 is particularly suitable for conventional timber partitions. By omitting top fixings of partitions for a distance of say 1.5 m from the partition junction the ceiling is able to horizontally flex the head of the partition. Because the torsional stiffness of partitions is much less than inplane stiffness the strength requirements of the driving elements are greatly reduced.

In the case of demountable partition or at junction between structure and partitions a sliding detail is usually provided. Simple junctions are not too difficult to deal with but in practice many complex situations are encountered and very close supervision and understanding of the problem by field supervisors is required to ensure success.

## 5. CODE PROVISIONS

### 5.1 Avoidance of Life Hazards

Life hazards may be the direct consequence of the failure of ceilings. They may also be an indirect consequence due to the loss of function of essential facilities e.g. hospitals. The operation of telephone exchanges has also been disrupted due to failure of ceilings. Failing ceilings additionally have a high potential for creating panic.

NZS 4203 : 1976[4], deals in some detail with the problem of suspended ceilings except where tiles weigh less than 2 kilograms each and are of such a shape and type as to be not capable of causing hazards. Clause 3.6.5 specifies that suspended ceilings, including integral lighting fixtures are to be designed for a loading of 0.6 g in any horizontal direction for class 111 (private) buildings.

A qualitative warning against nett upward forces due to vertical motions is given in the commentary clause C3.6.5. Connections to building and splices, in addition to the specified seismic load and gravity loads, must also be capable of transmitting certain minimum shears. To avoid failure caused by clearances formed due to the cumulative effect of deformations, limitations on deformations are specified.

UBC Standard, proposed Section 47.16, now probably implemented, requires for ceilings where the cross and main runners are in the same plane and no specific design been provided, restraint is to be provided by four No. 12 gauge wires fixed to the main runners adjacent to a cross runner and splayed 90° from each other at an angle not exceeding 45° from the plane of the ceiling. The bracing points where four wires are attached together at the main runner are to be at 4.2 m centres in both directions over the ceiling plane. Also, the ceiling perimeter may be attached to confining walls on two adjacent sides only, with clearance between the wall and runners on the other two sides.

The ATC-3, 1978 loading provision for the zone of highese seismicity varies from 0.24 g to 0.54 g.

Floor motion studies by Kelly[7] have shown that floor accelerations of 0.4 g are a fairly high Zone A probability in buildings yielding at 1.5 times the NZS 4203 code levels and may exceed 1 g in exceptionally strong motions.

### 5.2 Non Life Hazard Damage

There is still much opposition to codes concerning themselves with performance other than where life risks are involved. Understandably there is a long standing aversion to further legal interference and encroachment into the sanctity of private property. Nobody wants regulation excepting when it gives him personally more protection. Why should the code regulate matters that appear to involve economic consideration of the owner only? The answer should be affirmative because firstly present owners are not necessarily future owners. Most structures outlive their first owners and become the property of others. Also many are leased before they are sold. Material losses affect people other than the initial owner. Losses due to disruption of normal function of a building due to non-structural damage can be very high. When widespread in a city, months or even years may pass before the necessary resources are available to fully restore a building.

In one particular case, in which one of

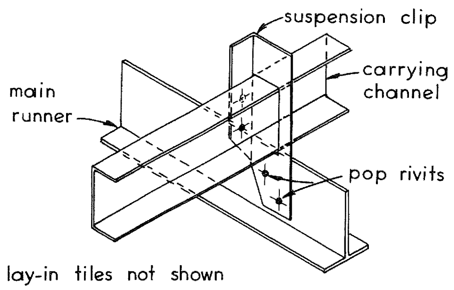


FIG 17
Carrying Channel/Main Runner Clip

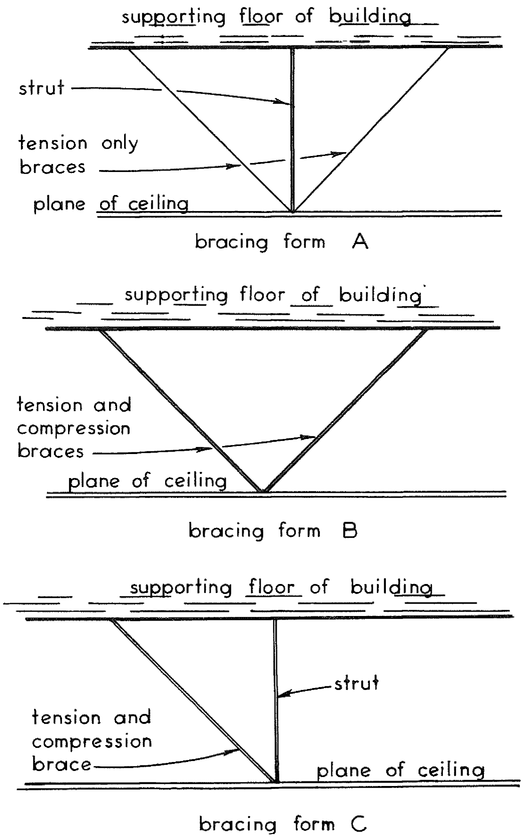


FIG 18
Bracing Forms

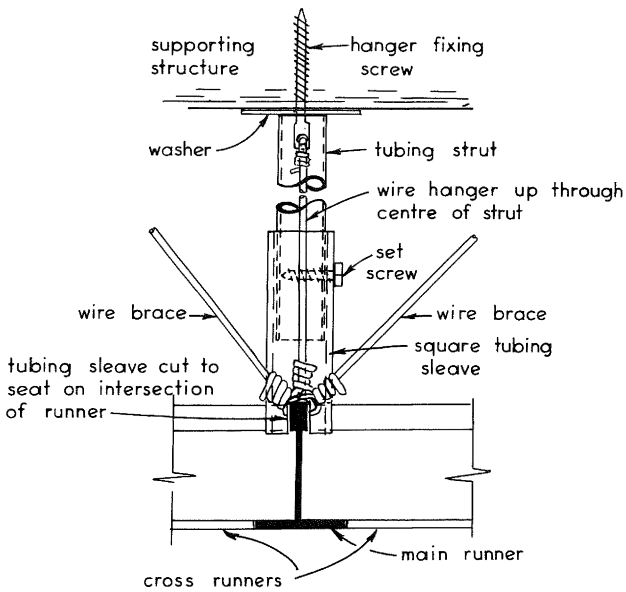


FIG 19
Vertical Strut at Bracing Point

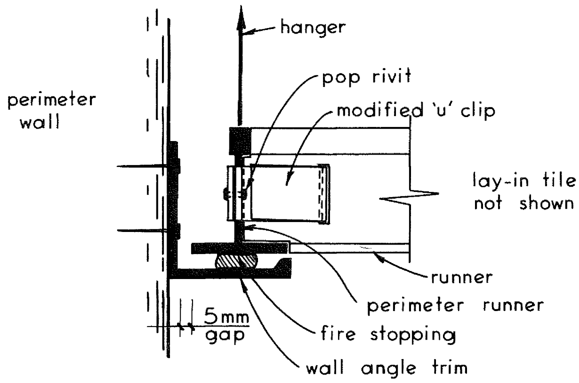


FIG 20
Ceiling Perimeter Detail with Fire Stopping

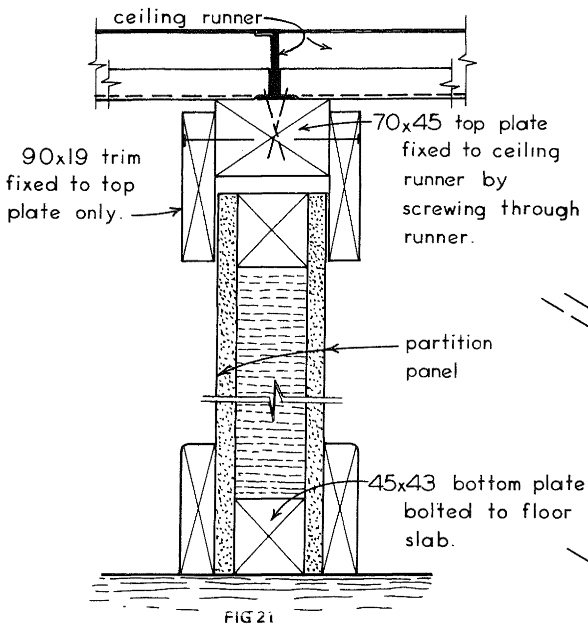


FIG 21
Ceiling/Partition Head Sliding Joint Cross Section

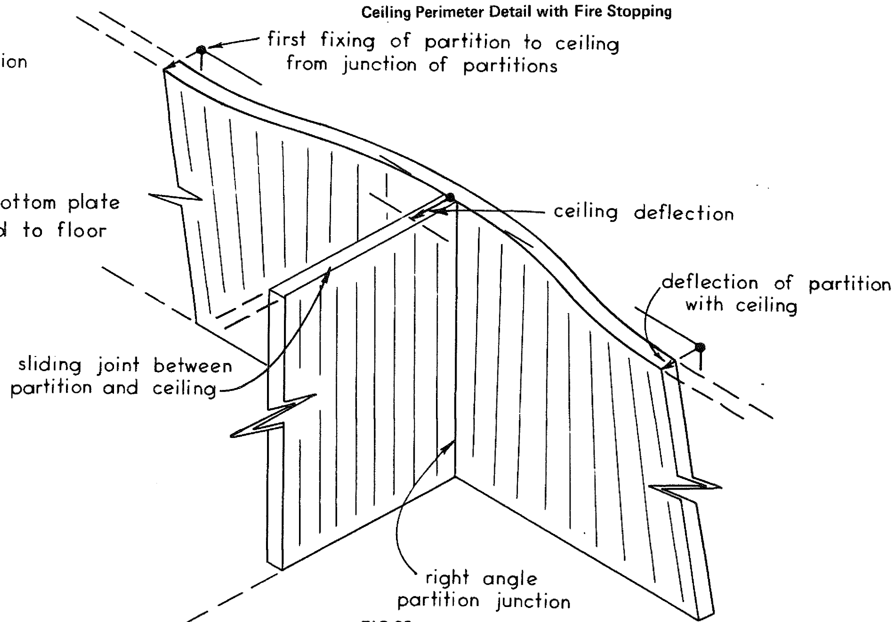


FIG 22
Right Angle Partition Joint

the writers himself assisted with an insurance claim, the loss of profits amounted to fifty times that due to direct damage. Notwithstanding the old maxim "buyer beware", because determination of the damageability of ceilings in an existing structure is difficult and time consuming and awareness of the potential risks limited to a few specialists, a lessee should not be expected having to arrange for an examination of his rented space by a structural engineer.

The final argument for code provisions to extend into the non life hazard damage area is that in the event of damage, the N.Z. Taxpayer will be required to foot the bill - after several years of errosion by inflation funds of the N.Z. Earthquake and War Damages Commission are very low in relation to the property value at risk. Alternatively high excess rates should be made to apply where designs do not include damage control measures.

## 6. THE ACCEPTABLE RISK

### 6.1 Life Hazard Risks

Where failure of the ceiling system is associated with significant life hazards, the acceptable risk should be comparable with that associated with total building failure. For these the design aim is currently that there should be a 90 percent probability of non-occurrence of total collapse. This is the equivalent to aiming at avoiding catastrophic failure in earthquakes that have approximately 500 year recurrence periods. Buildings designed to Code Design levels using current procedures may be expected to withstand earthquakes having effective peak accelerations (EPA's) possibly as great as twice those of the design earthquake, although some life hazards will develop at lower intensities.

In the seismically most active regions of New Zealand the expected mean return periods of earthquakes of intensities MMIX and X are 150 and 1,000 years respectively so that a 500 year return period earthquake is probably between IX and X in intensity. Notwithstanding the wide scatter in recorded values for MMVIII, an effective peak ground acceleration of the order of 0.2 g is a reasonable value on firm ground(9). The value of EPA for each step of MM changes by a factor of 2 for earthquakes below MMVIII. The increase is rather less than two-fold for each step above MMVIII. For the 500 year earthquake an EPA of about 0.4 g is therefore appropriate.

Fig. 23 is useful for studying economic and other risks associated with a particular design. In the x- directions displacements in terms of multiples of elastic displacements are plotted. In the y- direction are the accelerations levels that represent the mean peak responses of systems using the currently widely accepted assumption that effective peak ground accelerations will be amplified 2½ times by a building. Also shown are the intensities in MM numbers usually associated with such EPA's as well as the recurrence periods of such earthquakes appropriate for some regions of New Zealand(8).

Accelerations approaching the yield level of structures should therefore on average occur in the most active zones about every 15 years and result in top floor accelerations of 30 to 40% g in modern buildings.

While fig. 23 on the assumption that the equal displacement theorem holds may be used to determine displacements of a structure responding inelastically, the relationships between EPA of the ground motion and those in the structure no longer apply. Floor accelerations must in such cases be obtained from special studies(7).

It is important to consider the probabilities of occurrence of any event of recurrence period R in a given exposure time T. These are given by the expression

$$p = 1-e^{-T}/_R \text{ (or approximately } {}^T/_R \text{ when } {}^T/_R \text{ is less than 0.1)}$$

are shown on the right hand.

Consider for example a structure designed to yield at 0.15 g, i.e. Class III, zone A but with a real yield level of 0.2 g. The heavy line represents idealised response in the 500 year earthquake. The dotted line indicates the provisions for separation made if code requirements were just met i.e. for 2 x 0.15 g = 0.3 g response. If ceiling damage and consequently life hazards were caused in this building due to lack of separation, it is seen that in a 50 year period there is a high risk (approximately 85%) of a hazard developing. A design based on the other hand on 3½ times elastic displacement for avoiding damage i.e. equivalent 0.53 g elastic response, reduces the risk to 60% for a 50 year period. Damage is now unlikely except when an MM VIII or larger occurs, (i.e. at about 50 years on average).

If ceiling damage results from the acceleration response of the suspension system and the critical parameters of the input motion are known the risk can also be assessed from fig. 23.

### 6.2 Non-Life Hazard Risks: Economic Considerations

In the case of ceilings and partitions for which the Code does not require damage protection measures because they represent no significant life hazard risk e.g. lightweight ceilings, the decision to avoid damage must involve economic and other considerations. The results of any cost benefit study are heavily dependent on whose benefit is to be maximised. For the designer it is as a rule the benefit of his client but for society the issue is more complex (refer to Section 5.2).

Assume the most direct effects are to be included in the economic considerations only. The first step in the cost benefit analysis is an evaluation of the expected losses. Since not only the return periods of the earthquakes, but also the extent of losses of an earthquake of given period must be determined by a complex summation. Statistical data on return periods for MM values are usually given in terms that include with a particular event also all events of greater intensity. It is also reasonable to assume that in case of minor damage, repairs will be carried out without modifications that reduce risk of future damageability, but that following major damage, the vulnerable system will be replaced by a better one. The total loss in a given exposure time T is then given by[10].

$$E\,L(T) = \Sigma_n \, l_n \left(\frac{1}{R_n} - \frac{1}{R_{n+1}}\right) \left(1 - e^{-\frac{T}{R_{Mo}}}\right) R_{Mo} \qquad (1)$$

The first bracketed term gives the rate of the on-going process, the second term the probability of occurrence of $M_o$ in time T. $M_o$ is the MM intensity of the earthquake at or above which the ceiling will be replaced by a different system.

For a particular geographical location in New Zealand the set of (cumulative) returns periods $R_n$ (in years) and MM values shown below is reasonable. Loss ratios $l_n$ will vary for each case considered but statistical information is scarce. The following however will indicate the critical relationships and allow the order of losses to be determined.

| MM | n | $R_n$ | $\frac{1}{R_n} - \frac{1}{R_{n+1}}$ | $l_n$ | $l_n(\frac{1}{R_n} - \frac{1}{R_{n+1}})$ |
|---|---|---|---|---|---|
| VI | 1 | 6 | 0.117 | 0 | 0 |
| VII | 2 | 20 | 0.03 | .3 | $9 \times 10^{-3}$ |
| VIII | 3 | 50 | 0.0133 | .8 | $11 \times 10^{-3}$ |
| IX | 4 | 150 | 0.0056 | 1.0 | $6 \times 10^{-3}$ |
| X | 5 | 900 | 0.0011 | 1.0 | $1 \times 10^{-3}$ |
| | | | | | $\Sigma_n = 27 \times 10^{-3}$ |

Let $R_{Mo}$ be the return period of the event at or above which the system will not be reinstated in its original (deficient) form. If such an event takes place the hazard is effectively removed from the on-going process.

For an exposure period T = 1 year and $R_{Mo}$ = 50 years

$$E\,L\,(T) = 27 \times 10^{-3}(1 - e^{-1/50}) = 0.027$$

i.e. the annual risk is 2.7% of the replacement value. An insurance company would charge this as a premium plus loading for uncertainty, fluctuations and profit.

Annual risk can be computed by the following approximate calculations:

$E\,(L)$ for $T = 1$ $P = \Sigma\, l_n/R = 27 \times 10^{-3} = 0.027$ as above.

When longer exposure periods are considered the more complex equation must be used.

For T = 30 years and $R_{Mo} = 50$.

$$E\,L\,(T) = 0.027\,(1 - e^{-30/50})\,50 = 0.61.$$

The expected loss over 30 years is 61%. If such other losses as disruption of business etc. for a particular case are inappropriate to consider and if failure does not involve life risk then the aseismic damage design should not exceed the following fraction "k" of the initial cost:

$$Kx\,1.05^{30} - 0.61 \quad K = 0.14 \text{ (i.e. 14\%)}$$

otherwise it is cheaper to set aside a sum to pay for the damage when it occurs. To allow for the effect of inflation a low rate of return (5%) has been used to compound the sum set aside.

The real problem is more complex. Following a destructive earthquake, when damage is widespread both material and labour costs rise or repairs cannot be carried out at all for a lengthy period. Unless the money is invested overseas the effect on balance of payments could be severe. These wider issues must be considered and decided by society as a whole but it is the job of experts to bring them to its attention.

## 7. FUTURE WORK

In section 3.6 it has been shown that horizontal loadings in excess of 0.7 g can initiate vertical movements. When combined with vertical earthquake effects and high axial loads in some members the actions are difficult to predict and transverse wave formation must be expected at much lower responses than 0.7 g. Thus the behaviour of ceilings not restrained against vertical movements should be further investigated. The behaviour of other elements such as junctions of members is also difficult to predict analytically and should be the subject of dynamic testing. To a limited extent this has been done overseas[11] and also in New Zealand.

## 8. CONCLUSION

Integrated suspended ceiling systems subjected to earthquake motions have been shown to have a high potential for both life risk and economic losses unless very carefully engineered.

Notwithstanding the improvements that have been made in recent years, for any particular ceiling-partition system to perform adequately in a given building requires a good basic understanding of its intended performance by the designer field supervisor and erector.

The dynamic response of large ceilings in which upward vertical movements are not restrained is complex and should be the subject of further research and testing.

## 9. ACKNOWLEDGEMENT

The permission of the Commissioner of Works to publish this paper is acknowledged.

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This paper was presented at the South Pacific Regional Conference on Earthquake Engineering, May, 1979.