Post-Earthquake Performance of Sheet Bracing Systems

Introduction

Over the past ten months, the Canterbury region has been subjected to severe seismic activity. Seismologists have calculated that the two major events (4 September 2010 and 22 February 2011) have a return period of approximately 2500 years. In the 22 February 2011 event, ground accelerations of over 2 times gravity were recorded in both the vertical and horizontal directions. Ground accelerations of the magnitude recorded have resulted in structures being subjected to loads significantly greater than used for design.

Design Levels

In the design of residential structures, two design levels are considered:-

(i) The serviceability limit state design level
(ii) The strength or ultimate limit state design level.

In the design for the serviceability limit state, events occurring every now and again are considered. The loads used for this design level have a return period of 25 years for residential construction. In serviceability limit state deformations are usually considered. The amount of deformation is usually controlled in order that functionality of structure is not impaired and no damage is apparent. It is desirable that the structure remains in an elastic state during loading.

In the design for the strength or ultimate limit state, extreme events are considered. The loads used for this design level have a return period of 500 years for residential construction. In this design state, life safety is considered and the design is undertaken to prevent structural collapse and to ensure some level of functionality after the event.

The Design of Residential Structures for Earthquake Loading

The load exerted on a structure is a function of the mass of that structure. Residential structures have a short period of vibration, usually of the order of 0.3 to 0.4 seconds. The short period of vibration results in the structure being able to 'keep up' with the earthquake, hence the majority of the mass of structure is excited by the earthquake movement. Taller, multi storey structures tend to have longer periods of vibrations and are therefore unable to keep up with the high frequency earthquake movement resulting in less of the mass of structure being motivated during the earthquake.

In New Zealand, the design of structures to resist earthquakes is undertaken in accordance with NZS1170:5. Usually the equivalent static method of design is used. The design procedures given in NZS1170:5 were used to derive the earthquake bracing demand values given in NZS3604:2011.

In NZS3604 the bracing earthquake loads or demand are determined from the location of the structure, founding conditions, roof type, cladding type and plan area of the structure.

Derivation of Bracing Resistance Values for Light Timber Framed Structures

The bracing resistance values to be used for the design of light timber framed structures in accordance with NZS3604 are derived using the P21 testing procedures. These procedures were first published in 1984 (Cooney and Collins(1984)). The test arrangement was modified in 1987 and the evaluation method was changed to limit state format in 1991 (King and Lim (1991)). The test and evaluation method was revised in 2010 (Shelton (2010)). In this revision, frame sizes to be used in testing were specified, displacement levels used in cycling were also specified and the evaluation method was changed to reflect the requirement of AS/NZS1170.

The aim of P21 Test and Evaluation Method is to ensure that structures constructed with elements tested and evaluated using the method has sufficient strength and stiffness to sustain the loads that might occur every now and again and have sufficient reserves of strength in order that collapse does not occur during an extreme event. Typical test arrangements for the P21 test are shown in Figure 1

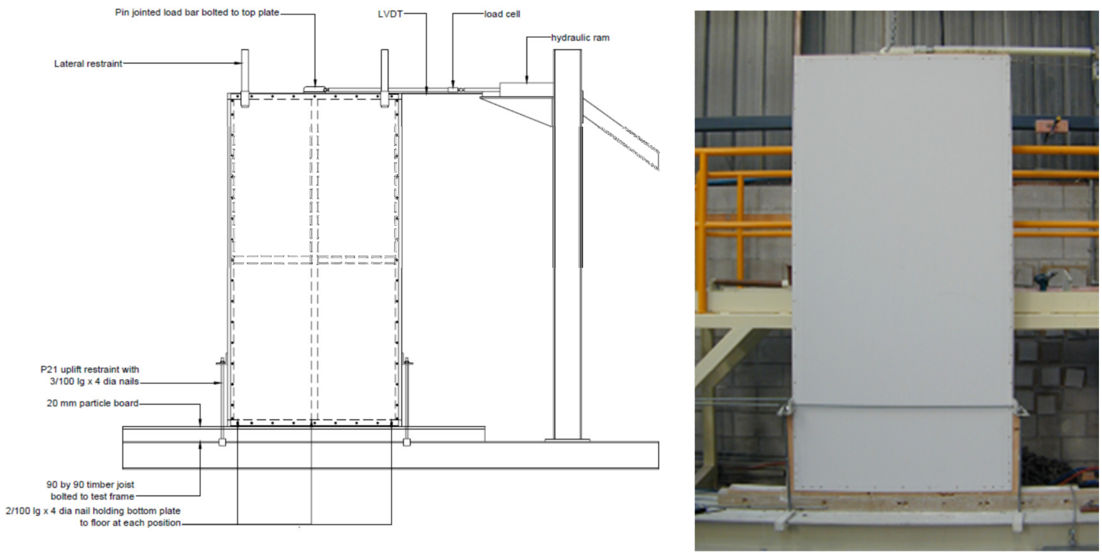
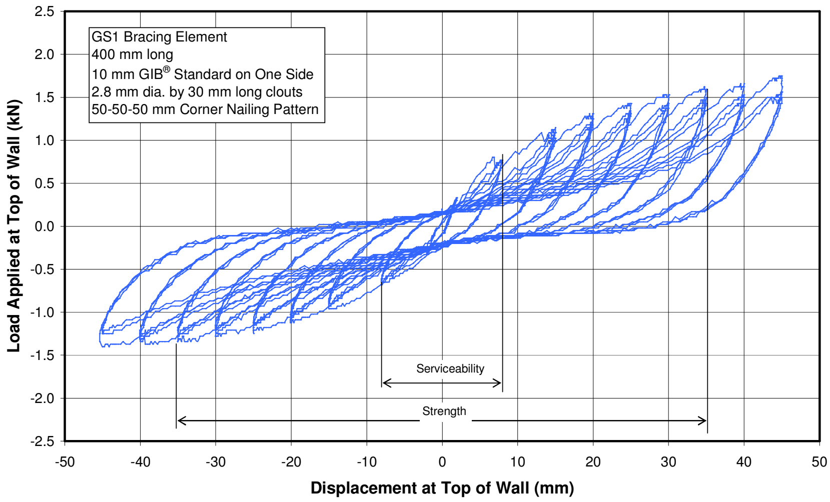


Figure 1
Typical P21 Test Arrangement

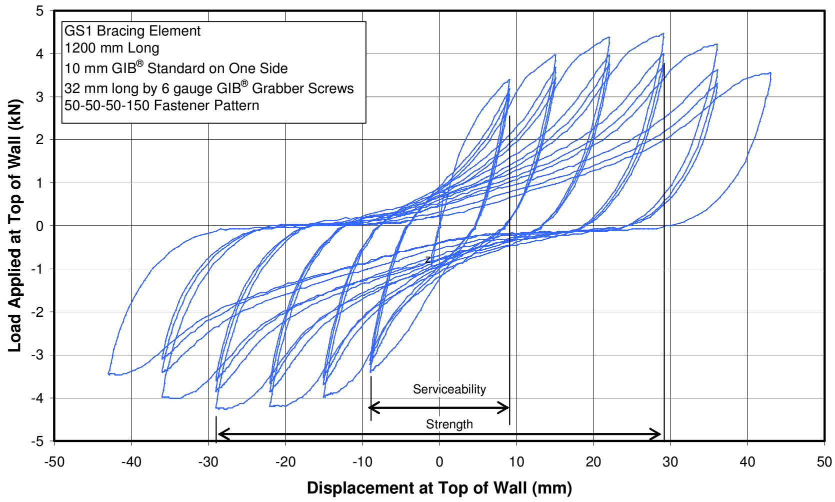
Behaviour of Sheet Bracing Elements in Timber Framed Structures

The behaviour of bracing elements are dependant on many factors including panel geometry, fastener type and panel hold-down arrangement. Panels lined with sheet material often exhibit similar behaviour when subjected to lateral loads. Short panels are often very flexible and exhibit semi-elastic behaviour. Little damage to the panels is observed even after loading to displacements expected during the extreme event. Long panels often sustain damage to the hold-downs and to the fasteners attaching the sheet material to the framing.

Typical load displacement plots recorded during a P21 test are shown in Figure 2. Also shown in Figure 2 are displacement levels for both the serviceability and strength limit state.



(a) 400 mm Long Element



(b) 1200 mm Long Element

Figure 2

Typical Load Displacement Behaviour of a Single Sided Plasterboard Panel

When a structure is loaded up to the serviceability limit there is little or no degradation in wall stiffness. However, if the structure is loaded beyond the serviceability limit there is significant degradation in stiffness. This type of behaviour is illustrated in Figures 3 and 4.

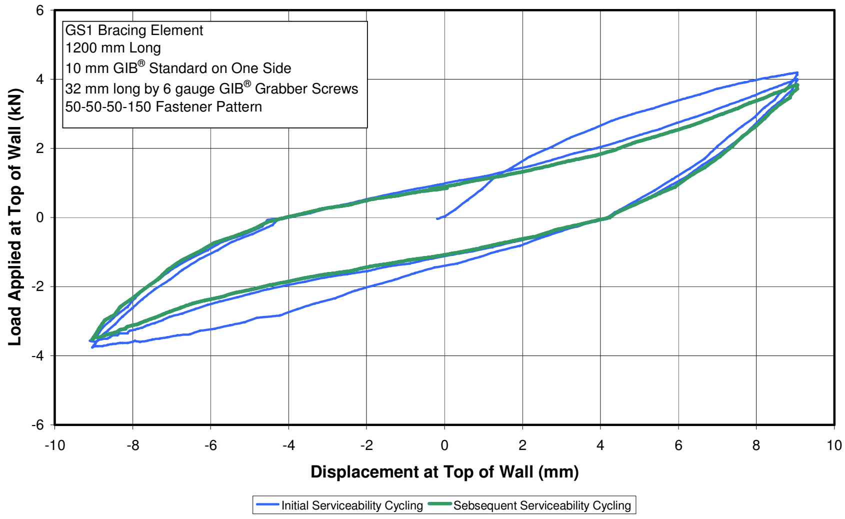


Figure 3
Typical Load Displacement During Initial and Subsequent Serviceability Events

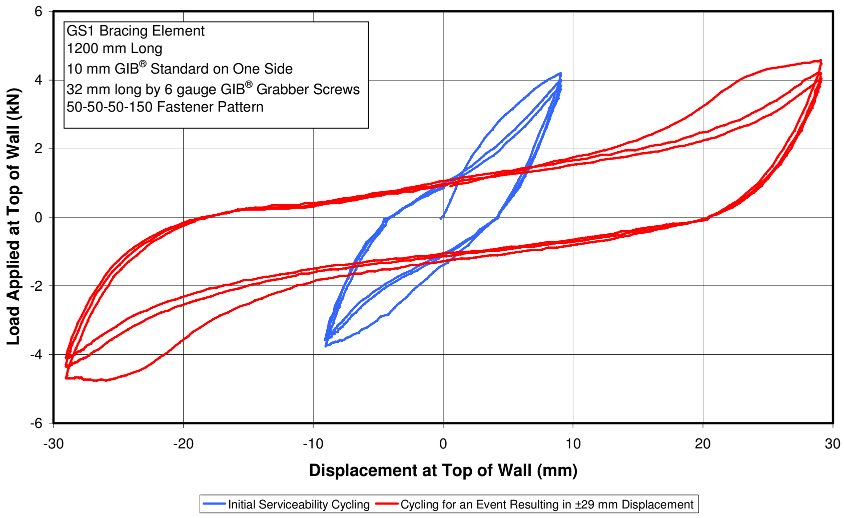


Figure 4
Typical Load Displacement Behaviour During Initial Serviceability Events and During An Event, Resulting in ±29 mm Displacement

In Figure 3, the load displacement behaviour of a GS1 bracing element during a typical serviceability event is shown. After the first cycle there is a very slight reduction in load carrying capacity but with subsequent cycling the load displacement response is approximately the same. In Figure 4, the load displacement behaviour of GS1 element is shown for an event resulting in ±29 mm displacement. Previously the bracing element had been subjected to events that resulted in displacements to ±9, ±15 and ±22 mm. The figure shows that to achieve the same load level that was recorded during the serviceability cycling;

the panel has to be displaced to approximately 22 mm in the first cycle and approximately 28 mm in the subsequent cycles to ±29 mm.

There is considerable anecdotal evidence in Christchurch that buildings tend to move considerably or make significant noises now (after the earthquake) as a result of vibrations from passing trucks, small gusts of wind and small ground movements. These observations can be partly explained by the reduction of the lateral stiffness of structure as a result of the structure being subjected to an extreme event. The reduction in stiffness can be illustrated in tests undertaken on bracing panels. In Figure 5 the serviceability load displacement behaviour of a GS1 bracing element is shown. Also shown in Figure 5 is the cycling to half the serviceability load after the element as been subjected to an event which resulted in a maximum displacement of ±36 mm.

The plots of Figure 5 show that prior to being cycled past the serviceability design load a displacement of approximately 4 mm would be expected when the element was subjected to a load of half the serviceability design load. After the element has been subject to an event resulting in a maximum displacement of ±36 mm, the element displaces approximately 23 mm when loaded to half the serviceability design load. This means the stiffness of the bracing element has reduced to approximately 20 % of the original stiffness.

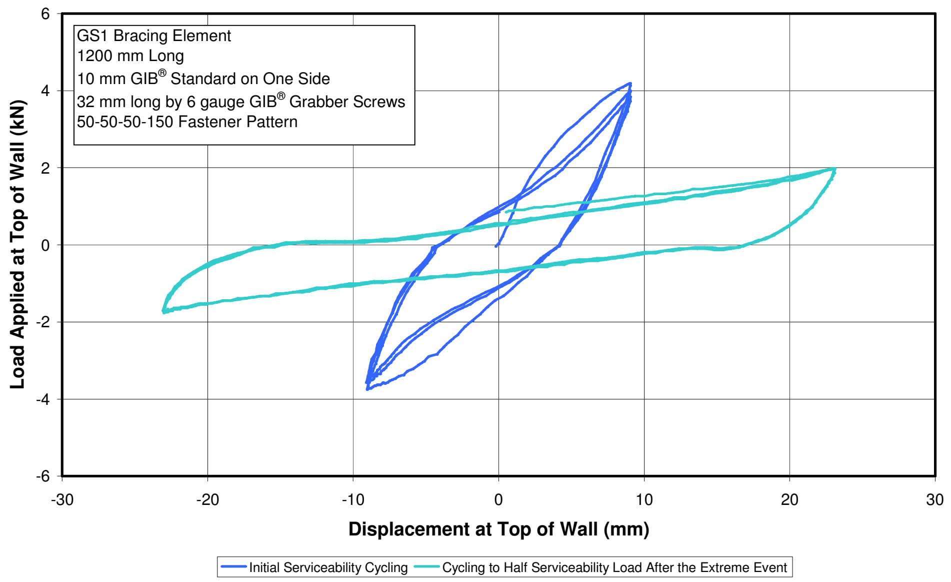


Figure 5
Typical Load Displacement Behaviour During Initial Serviceability Events and During Cycling to Half the Serviceability Load after An Event Resulting in ±36 mm Displacement

It is interesting to note that, although the stiffness of the bracing element has been considerably reduced, the overall strength of the element has not been significantly reduced. In Figure 6, load displacement behaviour of a GS1 bracing element is shown when it subjected to an event which results in a displacement of ±36 mm. Also shown in Figure 6, is cycling to ±36 mm (second extreme event) after the initial extreme event to ±36 mm. Figure 6 shows only a slight reduction in strength with subsequent cycling to ±36 mm.

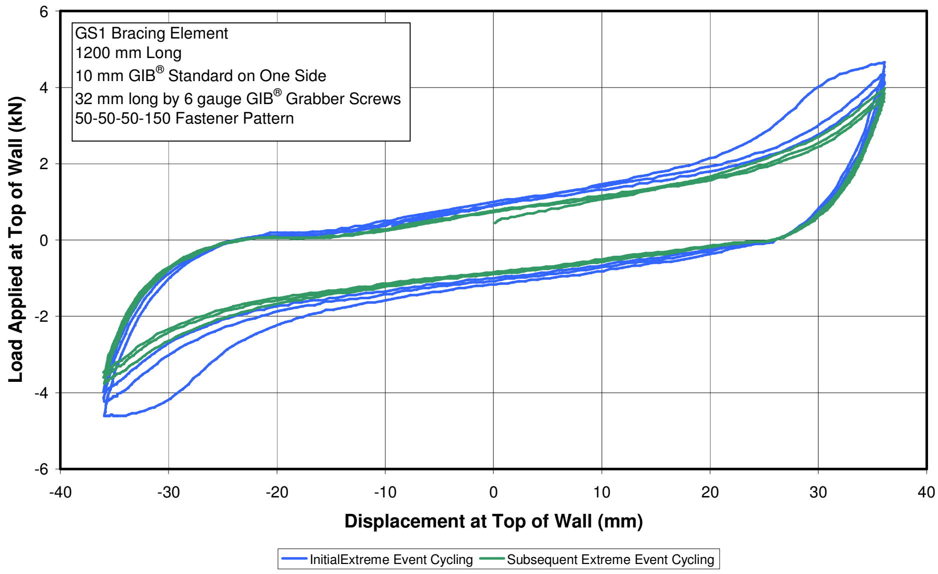


Figure 6
Typical Load Displacement Behaviour During Initial Event Cycling to ±36 mm and During Subsequent Event Cycling to ±36 mm Displacement

Plate 1
Plywood Bracing Element

The reduction in stiffness as a result of being subjected to an extreme event is not confined to plasterboard bracing systems. Most bracing systems behave in a similar manner. Set-in diagonal timber and steel braces and plywood bracing system will all reduce in stiffness when subjected to high loads and/or displacements. Most of the degradation in stiffness is a result of non recoverable (visco-elastic) deformation around the fasteners attaching the lining and/or brace to the framing. Non recoverable deformation can also occur around hold-downs connecting the framing to the foundation or sub-floor. In Figure 7, the serviceability load displacement behaviour of a plywood bracing element is shown. Also shown in Figure 7 is load displacement behaviour for cycling to half the serviceability load after the element as been subjected to an event which resulted in a maximum displacement of ±36 mm.

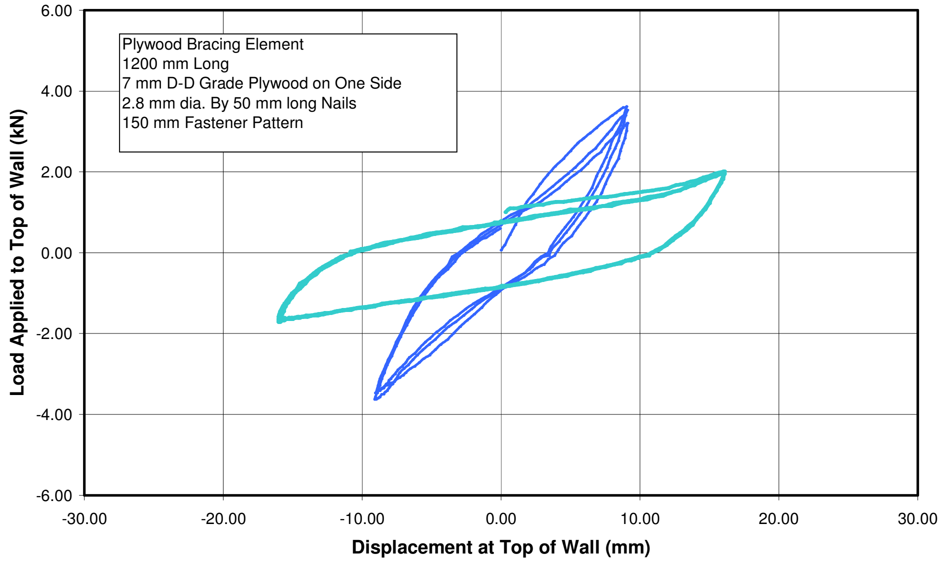


Figure 7
Typical Load Displacement Behaviour of a Plywood Bracing Element During Initial Serviceability Events and During Cycling to Half the Serviceability Load after An Event Resulting in ±36 mm Displacement

The behaviour of the plywood bracing element shown in Figure 7 is similar to that of the plasterboard bracing element. The stiffness of the element at half the serviceability design load after cycling to ±36 mm is approximately 25 % of the original stiffness. Little or no damage to the bracing element was apparent after testing.

Plate 2
Bottom of Plywood Bracing Element After Testing

Different Types of Damage to Plasterboard Bracing Elements

A number of different types of damage have been observed to plasterboard bracing elements. Damage falls into four main categories:-

(i) Cracking of linings,
(ii) Lining fastener movement,
(iii) Damage of the connection of bottom plate to floor system
(iv) Combination of the above.

Cracking of Linings

The formation of cracks in the linings as a result of earthquake movement is probably the most visible form of damage to plasterboard bracing elements. Cracks have often propagated from the corners of doors and windows. If there is a joint between the plasterboard sheets adjacent to the corner, then the crack will follow that joint. However if the plasterboard sheets are joined away from the corners of doors and windows (as suggested for best trade practise), then a diagonal crack forms in the plasterboard that extends from the corner into the field of the sheet.

(a) Crack of Joint above Door

(b) Diagonal Crack at Corner of Window

Plate 3
Cracking of Plasterboard around Doors and Windows

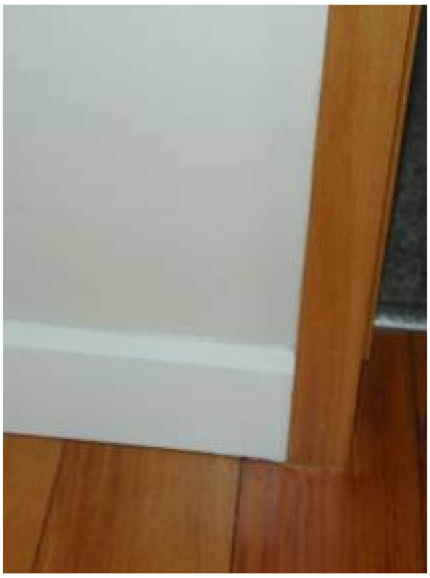
Lining Fastener Movement

Lining fastener movement as a result of earthquake forces can be easily identifiable or hardly visible. The movement can be such that fracture of the plasterboard along the line of fasteners can occur.

Plate 4
Fracture of Plasterboard along a Line of Fasteners

Fastener movement can result in popping of fasteners. In some cases this movement is readily identifiable but in other cases it is hardly distinguishable.

(a) Visible Fastener Movement



(b) Hardly Visible Fastener Movement

Plate 5

Damage of the Connection of Bottom Plate to Floor System

Damage of the connection of bottom plate to floor system can be the most difficult type of damage to identify as the movement as a result of this damage is often hidden behind skirtings or carpet. Damage can be a result of the bottom plate lifting away from the floor. In a GS type element this is a consequence of the fasteners pulling out of the floor system. This movement has been observed in a number of cases of GS type elements on concrete floors. When this type of movement has been identified, either after an earthquake or during testing, there is commonly little or no damage to plasterboard or framing.

(a) Element Uplift After Earthquake

(b) Element Uplift During Testing

Plate 6
GS Bracing Element Uplift

In some cases the studs have pulled away from the bottom plates. This results in damage to the plasterboard around the fasteners attaching the lining to the bottom plate. This damage is often hidden behind skirting.

Plate 7
Damage to Linings as a Result of Studs Separating from Bottom Plate

In plasterboard bracing elements with hold-downs, there can be considerable damage to the hold-down as a consequence of earthquake movement. The damage can cause the studs to move relative to the bottom plate resulting in considerable movement of the fasteners attaching the lining to the bottom plate.

(a) Damage to Hold-Down (b) Damage to Bottom of Sheet

Plate 8
Damage as a Result of Movement of Hold-Down

Repair of Plasterboard Bracing Elements

A number of factors have to be considered when the bracing elements are repaired. When a structure has been subject to an extreme event, damage is expected. The damage might be cracks in the linings, loosening of the fasteners attaching the lining, movement of joints in framing or loosening of hold-downs. The damage might not be readily identifiable. If the damage is not fully addressed during the repair to the structure then, when the structure is subjected even to a relatively minor event, the damage that has been repaired may be compromised and the structure might not perform adequately.

A number of different repair techniques were investigated. These repair techniques looked at improving the post extreme event stiffness and strength of bracing elements. The investigations included:-

- (i) Re-fastening the linings to the studs
- (ii) Re-fastening the entire boundary of the bracing element
- (iii) Overlaying the damaged lining with a new lining
- (iv) Replacing plasterboard sheet on plywood bracing element.

Re-fastening of Linings to Studs

In most residential structures scotia and skirtings are often present. These items are usually fitted adjacent to the top plates and bottom plates and hence prevent re-fastening of the plasterboard to the framing in bracing elements unless they are removed. To determine whether it is necessary to remove the scotia and skirting, a series of tests were undertaken to assess changes in performance when the bracing element linings were fastened to the edge studs and not to the top and bottom plates.

Load displacement behaviour during the serviceability cycles to ±9 mm and for the full test are compared to load displacement behaviour of the original panel in Figures 6 and 7 for a typical panel where studs have been re-fastened. In Figures 8 and 9, it is apparent there is little improvement in load displacement behaviour after re-fastening the lining to the studs. There was only a slight increase in stiffness during the serviceability cycles but the stiffness was still only approximately 30 % of the original stiffness.

During testing of these types of repaired bracing elements, it was observed that because of the poor connection of the lining to the top plate as a result of the original element being subjected to cycling to ±36 mm, the horizontal load was being transferred from the framing into the lining through the new fasteners attaching the lining to the top of the studs. As the cycling increased, the fasteners towards the top of the studs became distressed. In order for the horizontal load to be transferred, the fasteners further down the studs were required to transfer the load. This resulted in an unzipping effect of the lining from the studs.

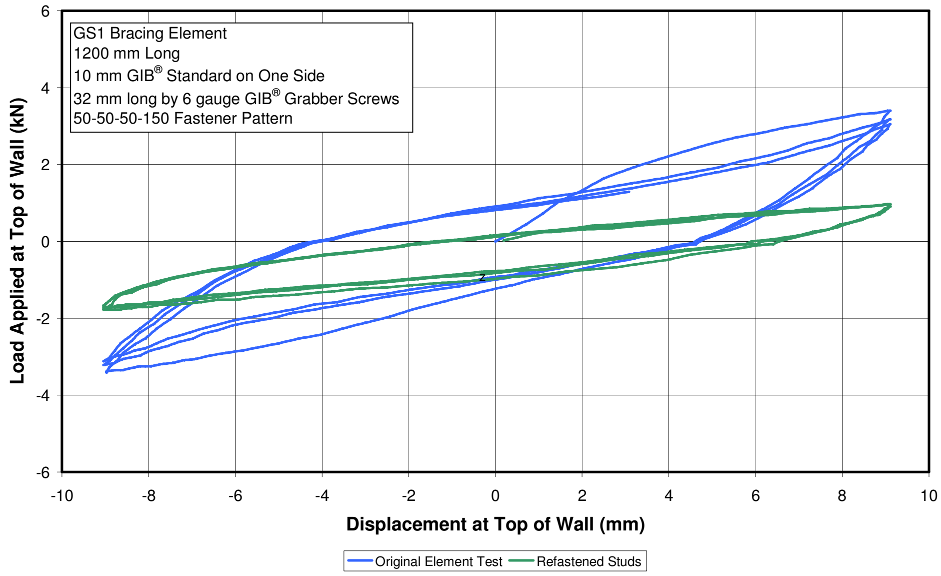


Figure 8
Typical Serviceability Load Displacement Behaviour of a GS1 Element before Extreme Event and After Refastening to the Edge Studs

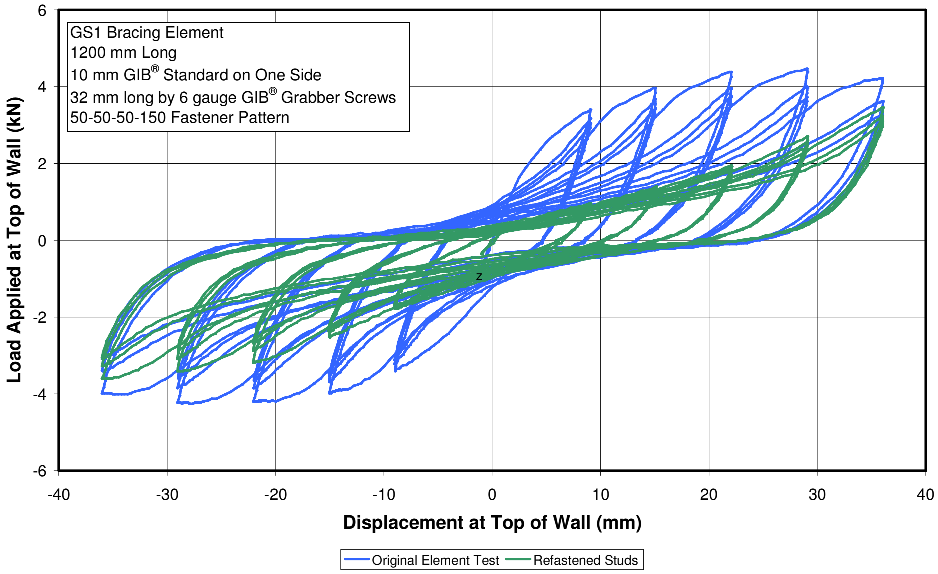


Figure 9
Typical Overall Load Displacement Behaviour of a GS1 Element before Extreme Event and After Refastening to the Edge Studs

Re-fastening of Linings around the Perimeter of the Bracing Element

Re-fastening the linings to just the edge studs did not result in any significant increase in the strength and stiffness of the bracing element. To check whether refastening the lining to the framing would improve performance, a series of tests were undertaken where the lining was refastened to the framing by placing fasteners midway between the existing fasteners right around the perimeter of the of the element. This method unfortunately requires the removal of scotia and skirtings in order to refasten the linings to the top and bottom plates.

For a typical panel where lining have been refastened to the framing, the load displacement behaviour during the serviceability cycles to ±9 mm and for the full test are compared to load displacement behaviour of the original panel in Figures 10 and 11. The load displacement plot of Figure 10 shows that refastening the linings has improved the stiffness of the element to approximately 80 % of the original stiffness.

During early the stages of testing of the elements, significant damage was observed around the fasteners attaching the lining to framing. Initially this damage was concentrated towards the bottom of the element but then spread to the fasteners on the top plate. This early damage around the fasteners could possibly explain why the full strength and stiffness of the element, as shown in Figure 8 and 9, was not achieved after refastening of the lining.

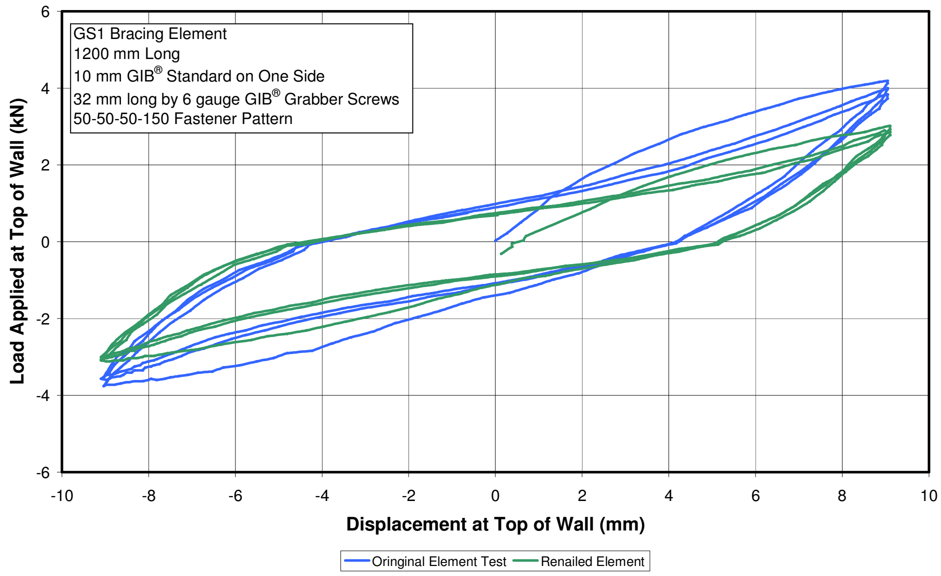


Figure 10
Typical Serviceability Load Displacement Behaviour of a GS1 Element before Extreme Event and After Refastening Lining to the Framing

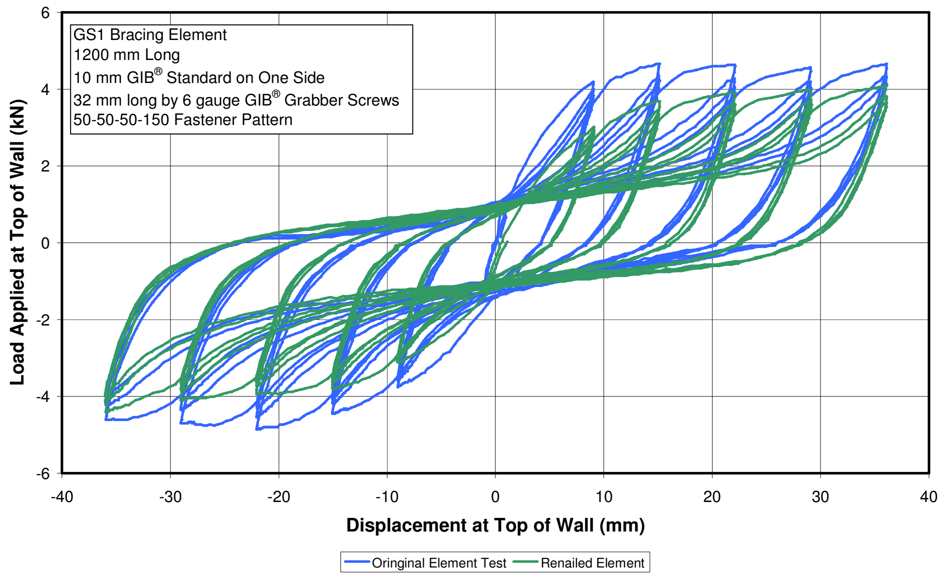


Figure 11
Typical Overall Load Displacement Behaviour of a GS1 Element before Extreme Event and After Refastening of Lining around the Perimeter of the Element

Plate 9
Refastened Bracing Element after Testing

Overlaying of Damaged Linings with New Linings

Another possible method of repairing earthquake damaged plasterboard bracing elements is to overlay the damaged lining with a similar lining. Overlaying of damaged linings would be attractive in situations where grooved jams are used. Firstly, Scoita and skirtings would need to be removed. The linings could then be fastened over the damaged linings. Architraves could then be placed around doors and windows and the skirtings and scotia replaced.

In order to ascertain whether it would be feasible to overlay, a series of tests were undertaken. In the tests, a second layer of 10 mm thick GIB® Standard was overlaid the damaged lining. This new lining was fixed with 41 mm long by 6 gauge screws. The screws were slightly offset from the original bracing pattern to insure they did not interfere with the existing fasteners below.

The load displacements plots of Figure 12 show that the serviceability behaviour of the original undamaged element is similar to the serviceability behaviour of the overlaid element. The overall load displacement behaviour for the original undamaged element is compared to the overlaid element in Figure 13. Figure 13 shows that the overlaid element has greater load carrying capacity when cycled at displacements greater ±15 mm. At a displacement of ±36 mm the load carrying capacity is approximately 20% higher for the overlaid element in comparison to the original element.

(a) After First Testing

(b) After Overlaying and Retesting

Plate 10
Typical Overlaid Bracing Element Before and After Testing

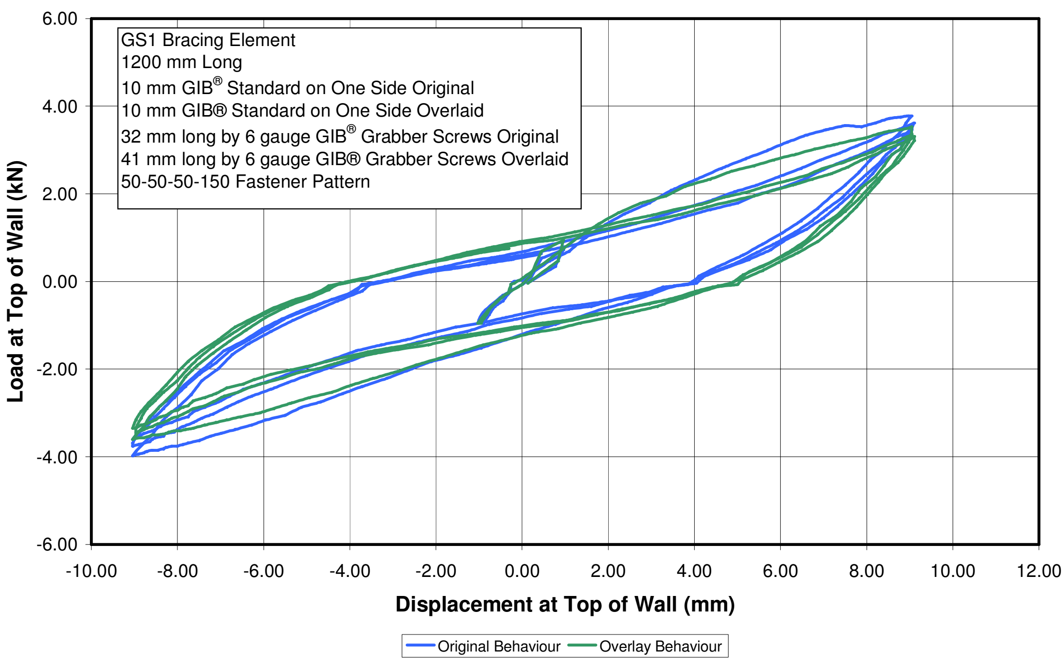


Figure 12
Typical Serviceability Load Displacement Behaviour of a GS1 Element before Extreme Event and After Overlaying of the Damaged Lining

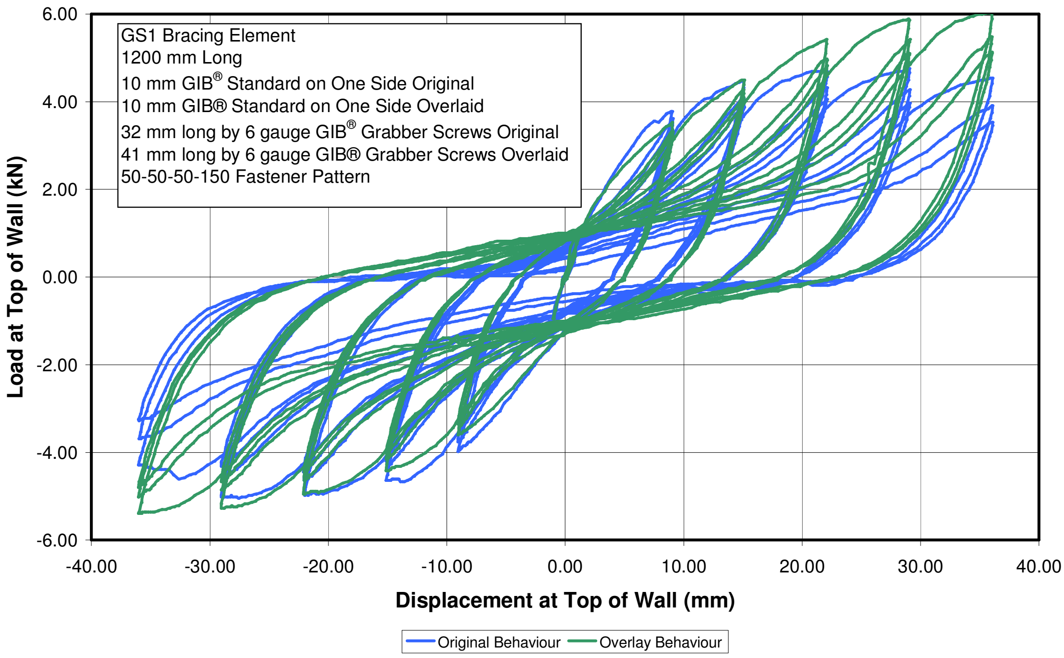


Figure 13
Typical Overall Load Displacement Behaviour of a GS1 Element before Extreme Event and After Overlaying of the Damaged Lining

Little damage to the overlaid sheets was observed after testing. The only damage was concentrated towards the bottom of the elements.

Plate 11
Typical Damage to the Bottom of Overlaid Bracing Element

Replacing Plasterboard Sheet on Plywood Bracing Element

In many cases the plywood sheets in plywood bracing elements are located on the external wall behind the brick veneer or other cladding systems. The location makes it very difficult to refasten the plywood back to the framing so that post extreme event stiffness characteristics of the element can be improved. A series of tests were undertaken to investigate what changes to the element's strength and stiffness characteristics when the plasterboard sheet was replaced on the inside of the framing. In this series of tests, GIB® Standard was placed on the inside of the element and fastened to the framing at 300 mm centres. In this case there is no consideration of possible damage to the bracing element.

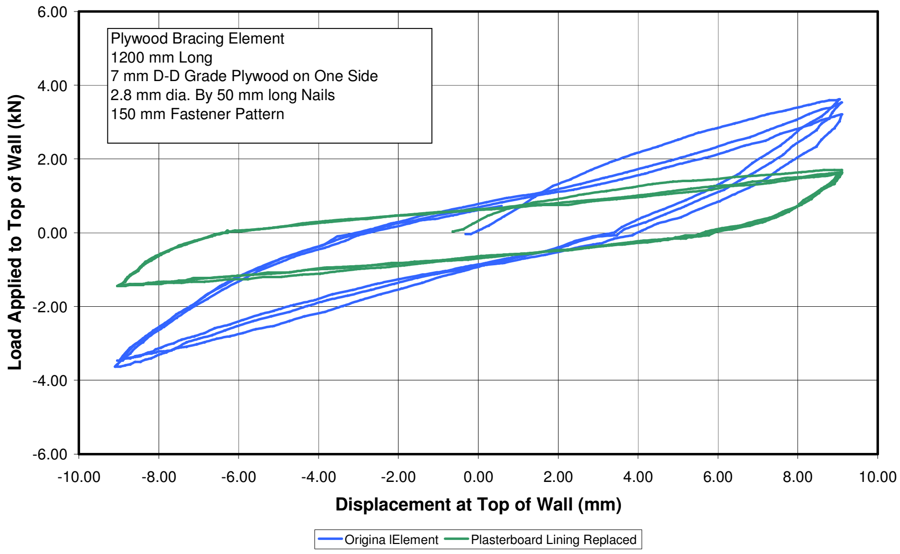


Figure 14

Typical Serviceability Load Displacement Behaviour of a Plywood Element before Extreme Event and After Replacing Plasterboard Lining

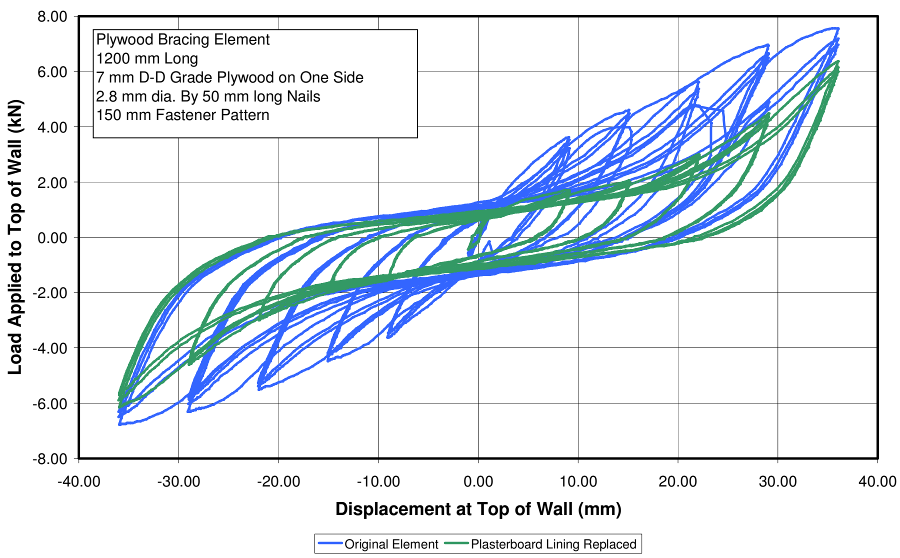


Figure 15

Typical Overall Load Displacement Behaviour of a Plywood Element before Extreme Event and After Replacing of the Damaged Lining

The load displacement plot of Figures 14 and 15 show that replacing the plasterboard lining (with the standard screw pattern) only slightly improved the post extreme event serviceability stiffness performance and did not effect the element overall strength characteristics. It clear from this series of tests that in order to improve both the stiffness and strength characteristic of the element the plasterboard needs to be screwed off as a bracing element and/or a special bracing lining such as GIB Braceline® need to be installed.

Other Considerations

In areas of considerable liquefaction, it has been observed that the depth of silt and water has been such that it is higher than the floor level of slab on ground houses. In these cases the silt and water has often entered into the brick cavity through the weep holes in the brickwork. In some cases the silt and water has penetrated the building wrap and flowed into the wall cavity saturating the insulation, framing and the back of the plasterboard linings. There have been a number of cases where the water has flowed into the house itself, saturating floor coverings etc. If this damage is not addressed when the structure is repaired, then there is the potential for mould growth and frame deterioration. The weep holes and cavity behind the brickwork should be cleaned out. The insulation should be removed and the frame also dried.

Plate 12
Liquefaction around a Brick Cavity House

In a number of dwellings, acrylic shower units have been cracked as a result of earthquake movement. This cracking is readily identifiable and will result in a leakage path for water if the shower is used. In a number of other houses, shower units have been formed by tiling over a waterproof membrane. It is difficult to assess if any damage has been done to these units and if there is now the potential for leakage resulting in the deterioration of the linings, framing and flooring.

Summary

As a result of a bracing system being subjected to an extreme event, the stiffness of that system is going to be considerably reduced. The reduction in stiffness must be addressed in any repair that is going to be undertaken. When considering the type and extent of repair a number of things should be considered:-

(i) Damage to hold-down system attaching the bracing element to the flooring. Careful inspection of the bottom of the element needs to be undertaken and if the hold-system is considered to be compromised, then linings should be removed and new hold-downs installed. If an overlay system is going to be used then the holes can be cut in the old lining and patched before fixing the overlay in order to facilitate the installation of new hold-downs.

(ii) If cracks have appeared in the field of the lining, then the lining should be removed and replaced. If cracks are along the joints then the old compound can be scrapped out, the linings refastened to the framing and new joint compound and tape placed in the joint. If an overlay is to be used, then no special attention needs to be paid to the old lining.

(iii) The bracing element should be re-fastened with appropriate fasteners. **If the sheet is *undamaged,* then the sheet can have fasteners placed mid-way between the existing fasteners. If the lining is only refastened to the edge studs, then only a small improvement in element stiffness is achieved. If the lining is refastened around the entire perimeter of the element, then the element stiffness is *approximately 80%* of the original element stiffness.** If, however, **an overlay** is used, then the element stiffness is similar to the original element stiffness and the element strength is increased. Longer fasteners (eg 41 mm instead of 32 mm fasteners) should be used when installing an overlay. These fasteners should be slightly offset from the existing fasteners.

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