CI/SfB			
Date: June 1998			

BRANZ
THE RESOURCE CENTRE FOR BUILDING EXCELLENCE

STUDY REPORT

No. 79 (1998)

THE VIBRATION PERFORMANCE OF TIMBER FLOORS

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The work reported here was funded by
the Building Research Levy.

ISSN : 0113-3675

PREFACE

This study investigates the applicability of a velocity-based assessment procedure for determining the dynamic suitability of timber floors. A portable procedure has been developed for exciting and measuring the dynamic response of timber floors. The research has highlighted the difficulties encountered in attempting to quantify a problem which has qualitative subjective judgements as an input.

ACKNOWLEDGMENTS

BRANZ is grateful for the assistance of Carter Holt Harvey Panels Ltd and Fletcher Wood Panels Ltd in this project through their donation of materials.

READERSHIP

This report is intended for researchers and engineers, to assist them to design timber floors without vibration problems.

THE VIBRATION PERFORMANCE OF TIMBER FLOORS

BRANZ Study Report SR 79 **G.J. Beattie**

Reference

Beattie, G.J. 1998. The Vibration Performance Of Timber Floors. Building Research Association of New Zealand. Study Report SR 79, Judgeford.

Keywords

Timber floors; Vibration; Serviceability; Dynamics

Abstract

Floor vibrations caused by people walking or running over a floor can result in serviceability problems. Problems encountered from these sorts of vibrations are usually annoying rather than structurally damaging, which makes the formulation of acceptance criteria difficult. There is no clear distinction between acceptable and unacceptable levels of vibration since personal sensitivities and highly variable external environmental factors combine to produce, at best, a fuzzy boundary of "acceptable" response.

Floor vibration problems are significantly influenced by the degree of damping present within the responding system. This is dependent on the material characteristics of the floor, its structural form, and the mass and character of the contents within the response zone and their spatial distribution, including both furniture and people.

This study attempted to apply a theoretical approach, developed by a Swedish researcher (Ohlsson), to commonly constructed New Zealand floors to predict their dynamic suitability. Three floors were subjected to impact loads from a soft bag filled with lead shot while their spans and other additions such as joist blocking and ceilings were varied. The first mode natural frequency of the floors, and the degree of damping, were used to estimate the suitability of the prediction from the Swedish model to New Zealand conditions.

It was found that adjustments to the Swedish model were required to the recommended cut-off criteria between "acceptable" and "unacceptable" behaviour before the model could be applied to the tested floors. Further research is required to reconcile qualitative assessments of the suitability of floors against the quantitative predictions of the model.

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Prediction of the vibration performance of timber floors with joists is an area fraught with difficulty because of the subjective nature of the assessment. There is no clear distinction between acceptable and unacceptable levels of vibration, since personal sensitivities and highly variable external environmental factors combine to produce, at best, a fuzzy boundary of "acceptable" response.

This study attempted to apply a theoretical procedure, developed by Ohlsson (1988), to commonly constructed New Zealand floors to predict their dynamic suitability. Three floor specimens were constructed in the laboratory and subjected to impact loads from a soft bag filled with lead shot dropped onto the floor from a height of 500 mm. Their joist spans and other additions such as joist blocking and ceilings were varied. Floor accelerations were recorded and analysed to determine the first mode natural frequency and the degree of damping. Limited subjective assessment of the vibration annoyance was also undertaken.

For all the floors, the following general observations on dynamic behaviour were recorded:

- Reducing the span had the effect of increasing the first mode natural frequency, especially when the overhanging ends of the floor were propped.

- The addition of blocking increased the first mode natural frequency - two rows of blocking did not change the first mode natural frequency from the one row of blocking case although higher modes were more significantly affected.

- Propping the outermost joists to simulate four sided support significantly stiffened the floors and increased the frequency responses as a consequence.

- The addition of ceiling battens and ceiling lining caused little change to the first mode natural frequency because the additional stiffness was offset by the extra mass.

- Higher frequency modes were influenced by the addition of the ceiling.

- Damping ratios for the bare floors tended to be about 2%.

- The presence of one person on the floor mildly increased the damping.

- The presence of four people significantly increased the damping.

With respect to the floor which had glued and nailed joints between the flooring and the joists:

- Gluing the flooring to the joists caused little change to the natural frequencies of the floor from the unglued case.

- The addition of carpet and underlay did little to alter the natural frequencies and damping of the floor.

- The addition of rigid inanimate mass to simulate furniture caused a reduction in the first mode natural frequency but did nothing to alter the damping.

- Excitation of the cantilever section of floor produced a first mode natural frequency at the centre of the simply supported span that was approximately 4 Hz less than the same span with no cantilever, due to the dynamic oscillation of the cantilever section.

With respect to the floor which had a timber strongback temporarily attached to the joists at mid span:

- The addition of a strongback made little difference to the natural frequencies or damping.

The application of the Ohlsson procedure to predict the dynamic behaviour required an assessment to be made of the effectiveness of connections between the flooring and the joists, the blocking and the joists and the ceiling and the joists. Some conservative generalisations on these effectiveness's were made from the comparison between the experimental results and the prediction using Ohlsson's procedure. The following parameter values are suggested for use when the suitability of new floors is being assessed by this method:

- When installed in conjunction with ceiling battens and plaster based ceiling lining, the effectiveness of one or two rows of blocking in spreading the load can be assumed to be at least 70%.

- The effectiveness of the ceiling battens and plaster ceiling lining in spreading the load can be assumed to be approximately 45%, provided there is at least one row of blocking present.

- One row of blocking and no ceiling can be assumed to be approximately 40% effective.

- Two rows of blocking can be assumed to be at least 50% effective when there is no ceiling present.

- The deck continuity percentage appears to range from 20% at 3.2m span up to 60% at 4.8m span.

- The addition of adhesive between the deck and the joists does not make the deck any more effective than when there is no adhesive.

Anomalies were found in the predictions of acceptable performance using the Ohlsson procedure. If the constant term in Ohlsson's equation for determining the cutoff point between good and unsatisfactory behaviour is changed from 10 to 2 and the damping is increased from 1% to 2%, Ohlsson's prediction is slightly less conservative than Chui and Smith's prediction (1990) and yields spans slightly greater than NZS 3604 allows.

The difficulty with the validation of any of these predictions is that a subjective judgement is required by people using the floor. In the limited experimental work undertaken in this study, it appeared that the spans predicted using a constant of 2.0 and damping of 2% were acceptable. Further work is required to obtain unbiased subjective assessments of the performance of a range of New Zealand floor spans so that the modified Ohlsson prediction can be validated.

1. INTRODUCTION

The object of this investigation was to prepare a modified set of joist span tables for NZS 3604 (SNZ, 1990) to take account of the serviceability effects of vibration and in the process, develop a portable test procedure for the assessment of existing timber floors.

Building vibration effects which result in serviceability problems are often classified by the duration over which they occur. Long term vibrations are classified as "continuous" while short term effects are known as "transient". The cause, the acceptance criteria and the treatment of each is different. Continuous vibrations can be caused by vibrating machinery such as air conditioning units and are more often found in commercial buildings than domestic. Transient vibrations are those more normally encountered in domestic construction. They can be caused by intermittent excitation sources which often include a spatial variance component (eg people walking or running over floors). These impulses generate a combination of responses within the floor system which include quasi-resonant effects and direct impulse responses.

Problems encountered from transient vibrations are usually annoying rather than structurally damaging which makes the formulation of acceptance criteria all the more difficult. There is no clear distinction between acceptable and unacceptable levels of vibration since personal sensitivities and highly variable external environmental factors combine to produce, at best, a fuzzy boundary of "acceptable" response. For example, a seated person may perceive a dip in the floor as another person walks by or crockery may rattle. For one person, the movement or rattle may be of no consequence whereas another may be quite disturbed by the event. Transient vibration problems are significantly influenced by the degree of damping present within the responding system. This will be dependent on the material characteristics of the floor, its structural form, and the mass and character of the contents within the response zone and their spatial distribution, including both furniture and people.

2. LITERATURE REVIEW

A report has been prepared by BRANZ (King,1997) which contains a guide to the serviceability limit state criteria for New Zealand buildings. To design against unacceptable vibration, it was suggested that a floor with a static load of 1 kN deflecting no more than 1.5 mm was a suitable serviceability limit. The 1.5 mm has been relaxed from 1 mm as suggested in Table C2.4.1 of NZS 4203 (SNZ,1992). This is consistent with the deflections encountered within currently used timber floor joist span tables, but is more restrictive than the dynamic serviceability requirements stated in AS 3623 (SA,1993). Regardless of the static trigger value, it is the dynamic response, particularly the natural frequency of the floor system, which dictates its acceptability. More detailed methods of evaluating the acceptability of floor systems are described later in this report. The results from this more detailed study should be considered to be more accurate than the acceptance guide and should be given priority.

Two methods have been described by King (1997) for calculating the vibration response of floors. The calculated responses are compared against acceptance criteria in the form of graphical presentations of either peak accelerations or unit impulse velocities versus natural frequency.

The first of these methods was developed by Allen and Murray (1993) to apply to commercial type buildings (concrete or steel frames with reinforced concrete decks) which have a natural frequency less than 9 Hz, and this method is therefore not relevant to timber floor systems with joists. Ohlsson (1988) developed the second method which specifically related to domestic style joist floor systems. The acceptance criteria apply only to floors with a natural frequency greater than 8 Hz. This method has subsequently been included in Eurocode 5 (European Committee for Standardisation, 1993).

A further method was proposed for timber floors by Chui and Smith (1990), in which the root-mean-squared acceleration of the floor was required to be less than 0.45 m/s^2 and the first mode natural frequency to be greater than 8 Hz for the floor to be dynamically acceptable.

3. EXPERIMENTAL INVESTIGATION

3.1 Details of the Test Floors

Three floors were constructed for the investigation. Floors 1 and 2 had nominal 200 mm x 50 mm joists and the third had 140 mm x 45 mm joists. All floors had 20 mm thick high density particle board flooring fixed to the joists with 60 mm x 3.15 mm diameter galvanised gun nails at 150 mm centres around the perimeters of all sheets and at 300 mm centres on intermediate joists. Continuous boundary joists of the same cross section were installed at both ends of the joists with 100 mm x 4 mm diameter nails connecting joists to boundary joists to stiffen the floors for easy lifting into position on the test rig. The floors were constructed with joist spans made purposely longer than the maximum spans allowed in NZS 3604:1990.

Solid 100 mm x 50 mm blocking on the flat was installed at sheet joints that were at right angles to the joist span direction. In normal practice, the solid blocking used to improve transverse stiffness would be placed under the sheet edges wherever possible to save material usage. However, in the test floors, it was known that the blocking would be changed over the course of the investigation and therefore could not be relied on to always be at the sheet joints.

Part of this study was aimed at examining the effect that gluing the flooring to the joists had on their behaviour. So that a comparison could be made between the nailed and the glued and nailed floor response, for Floor 2 only, slots were cut in the top surface of the joists prior to assembly. The slots were 5 mm wide by 3 mm deep by 100 mm long and spaced at 300 mm along each joist. Before the flooring was laid, 5 mm diameter holes were bored through the flooring to correspond with the ends of each slot. Once the nailed-only tests had been completed, adhesive was injected with a caulking gun into the hole at one end of each slot until it was observed in the hole at the other end. The plan area of the slot was designed to simulate a "daub" of adhesive placed at 300 mm centres along the joists during normal construction. It was subsequently found that the adhesive shrunk markedly once installed and therefore lost contact with either the flooring or the joist over a significant area of the slot. However, there was also a significant unexpected penetration of adhesive into the surrounding space between the joist and the flooring which helped to simulate the field conditions more accurately.

Floor 3 was constructed with no full depth blocking at the mid span of the floor. Instead, once the floor was installed on the supporting walls, a strongback of 140 x 45 timber was attached with angle brackets to the underside edge of each of the joists at their mid span in an effort to obtain a comparison between floor performance with full depth blocking and the case with the strongback.

Details of the floors, as initially constructed, are presented in Figures 1 to 3. Notes about alterations to the floors during the experimental work are contained in the figures.

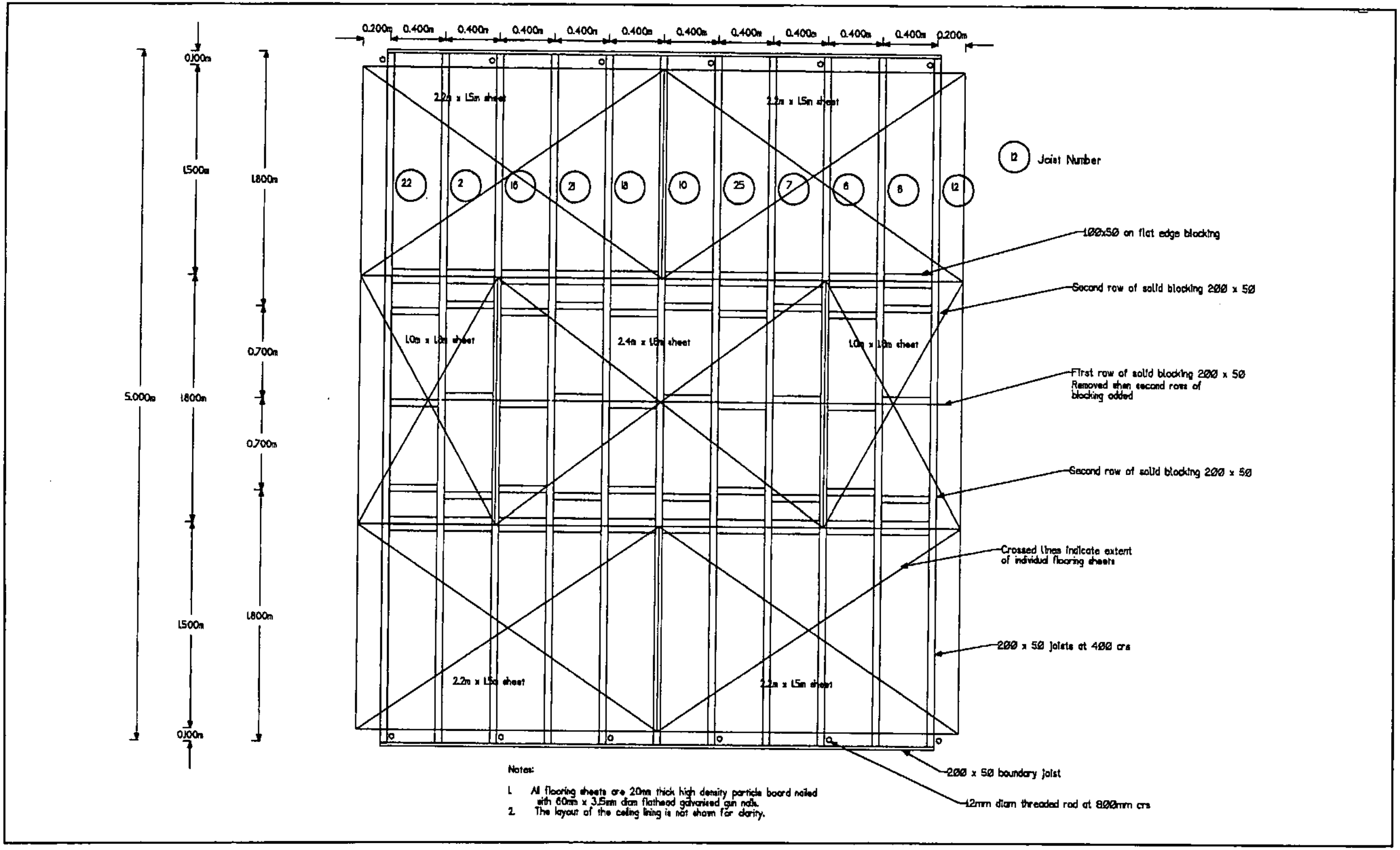

Figure 1: Details of Floor 1 Setup

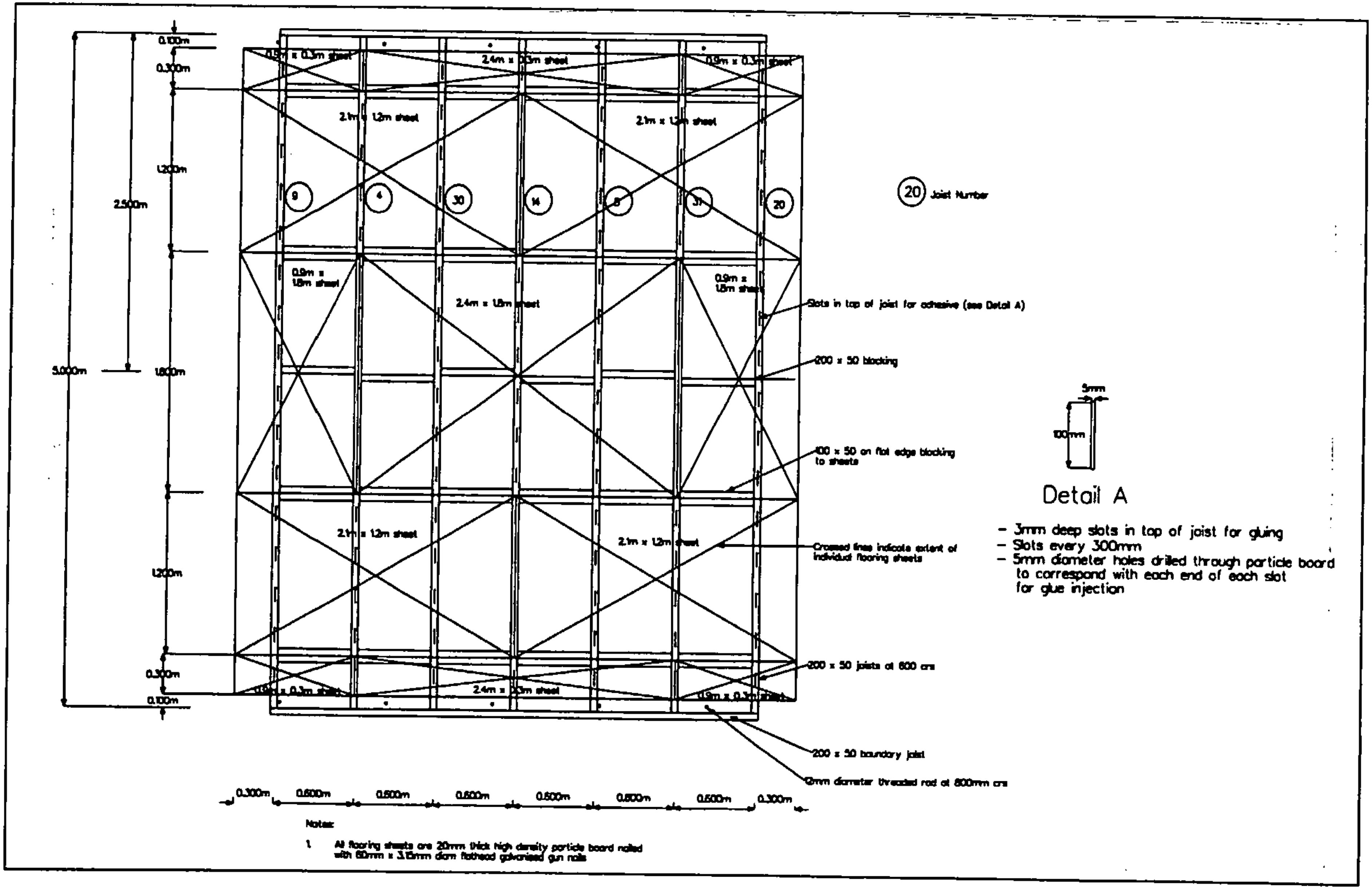

Figure 2: Details of Floor 2 Setup

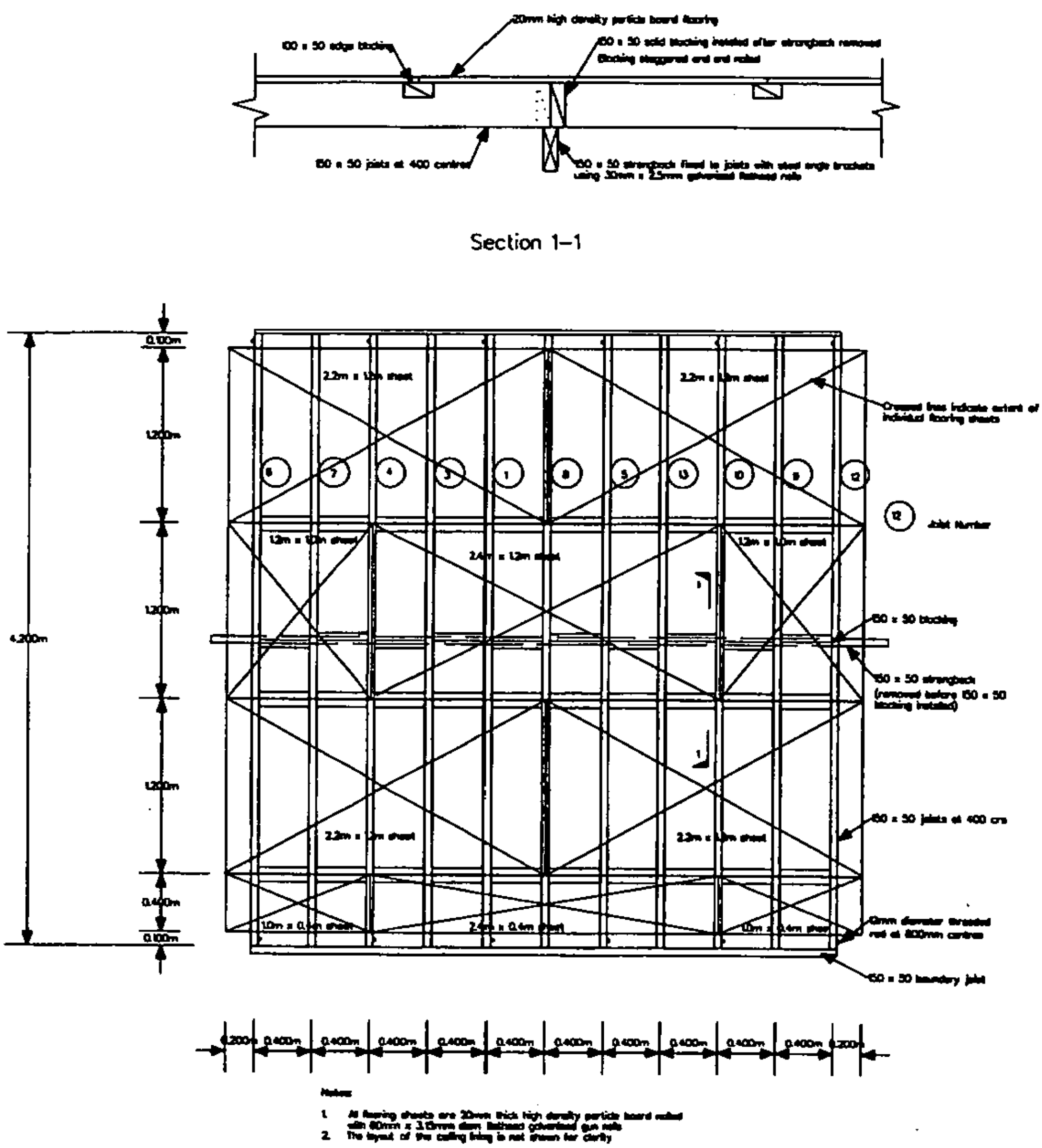

Figure 3: Details of Floor 3 Setup

Prior to assembling the floors, all individual joists were subjected to a two point bending test in accordance with the BRANZ structural test procedure ST18 (BRANZ,1994), to obtain the Modulus of Elasticity of the individual sticks. The procedure is used in conjunction with AS/NZS 4063 (SA,1992). The modulus of elasticity values are presented in Table 1.

Table 1: Modulus of Elasticity of Component Joists

Floor Number	Joist Position in Floor w.r.t. centre joist	Nominal Stick Size (mm x mm)	Stick Ident. Number	Modulus of Elasticity (GPa)
1	2.0m west	200 x 50	22	9.6
1	1.6m west	200 x 50	2	9.8
1	1.2m west	200 x 50	16	9.1
1	0.8m west	200 x 50	21	10.1
1	0.4m west	200 x 50	18	8.4
1	Centre	200 x 50	10	11.3
1	0.4m east	200 x 50	25	8.7
1	0.8m east	200 x 50	7	10.9
1	1.2m east	200 x 50	6	9.0
1	1.6m east	200 x 50	8	9.9
1	2.0m east	200 x 50	12	9.4
				Mean = 9.7
2	1.8m west	200 x 50	9	9.8
2	1.2m west	200 x 50	4	10.5
2	0.6m west	200 x 50	30	8.7
2	Centre	200 x 50	14	11.1
2	0.6m east	200 x 50	5	8.8
2	1.2m east	200 x 50	31	10.1
2	1.8m east	200 x 50	20	9.3
				Mean = 9.8
3	2.0m west	150 x 50	6	8.0
3	1.6m west	150 x 50	7	8.1
3	1.2m west	150 x 50	4	6.9
3	0.8m west	150 x 50	3	8.4
3	0.4m west	150 x 50	1	6.3
3	Centre	150 x 50	8	9.1
3	0.4m east	150 x 50	5	6.0
3	0.8m east	150 x 50	13	8.6
3	1.2m east	150 x 50	10	7.4
3	1.6m east	150 x 50	9	8.3
3	2.0m east	150 x 50	12	7.9
				Mean = 7.7

To achieve a reasonable uniformity of joist stiffness across each floor, the joists were ordered as shown in Table 1, from one side of the floor to the other.

Support for the floors was provided by a pair of timber framed walls 1 metre high. These walls were braced out-of-plane to the floor of the laboratory and were free to move in the direction of the joist spans so that the span of the floors could be varied.

A cross section through the supporting walls is shown in Figure 4. Two 200 x 100 rolled hollow section strongbacks and 12 mm diameter threaded rods were used to clamp the test floor to the top of the supporting walls. The rods were tensioned by tightening the holddown nuts by three turns beyond finger tight.

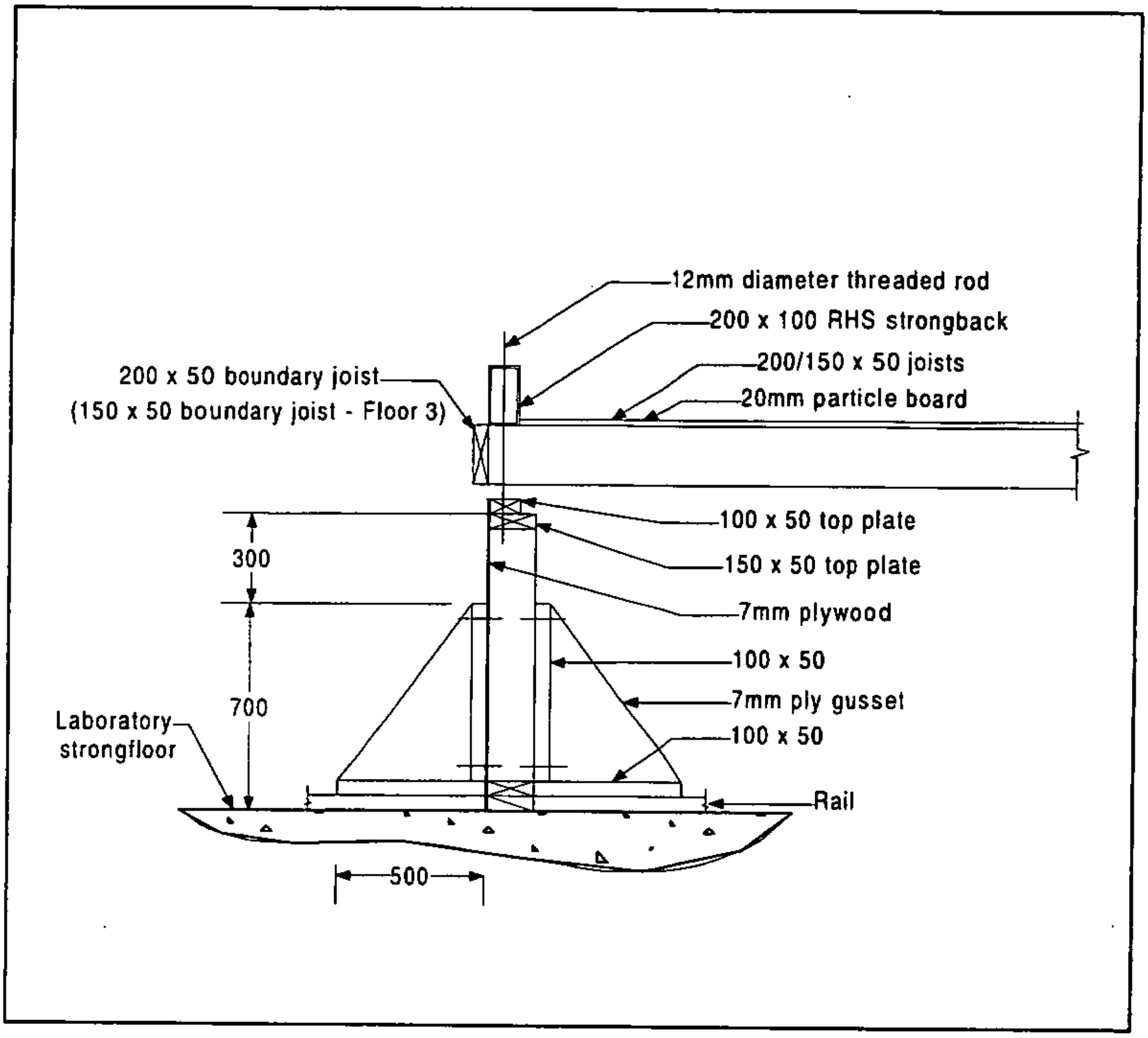

Figure 4: Cross section through the supporting walls

3.2 Instrumentation

3.2.1 Static deflection measurements

For the static tests joist deflections were monitored with 50 mm dial gauges capable of being read to 0.01 mm and accurate to 0.05 mm. Deflections for Floor 1, up to dynamic test number 81, were monitored at five positions, these being at:

- the mid span at the central joist
- the third joist out from the centre in each direction
- the outside joists

From dynamic test number 82 onwards, the deflections were monitored at the centre joist and the four adjacent joists to one side.

For Floor 2, the static deflections were recorded at the centre joist, the three joists to one side of the centre and the adjacent joist on the other side of centre.

The number of joists on Floor 3 was the same as Floor 1 and so the deflection gauges were set up under the same joists as in Floor 1 dynamic test 82 onwards.

3.2.2 Dynamic acceleration measurements

Generally, three acceleration measurements were made on each floor. Accelerations were recorded at the mid span of the centre joist and at the third joist out from the centre on each side (1.2m out) for Floor 1 and Floor 3. For Floor 2, the accelerometers were installed at the mid span of the centre joist and at the second joist out from the centre on each side (1.2m out). Locations are shown in Figure 5.

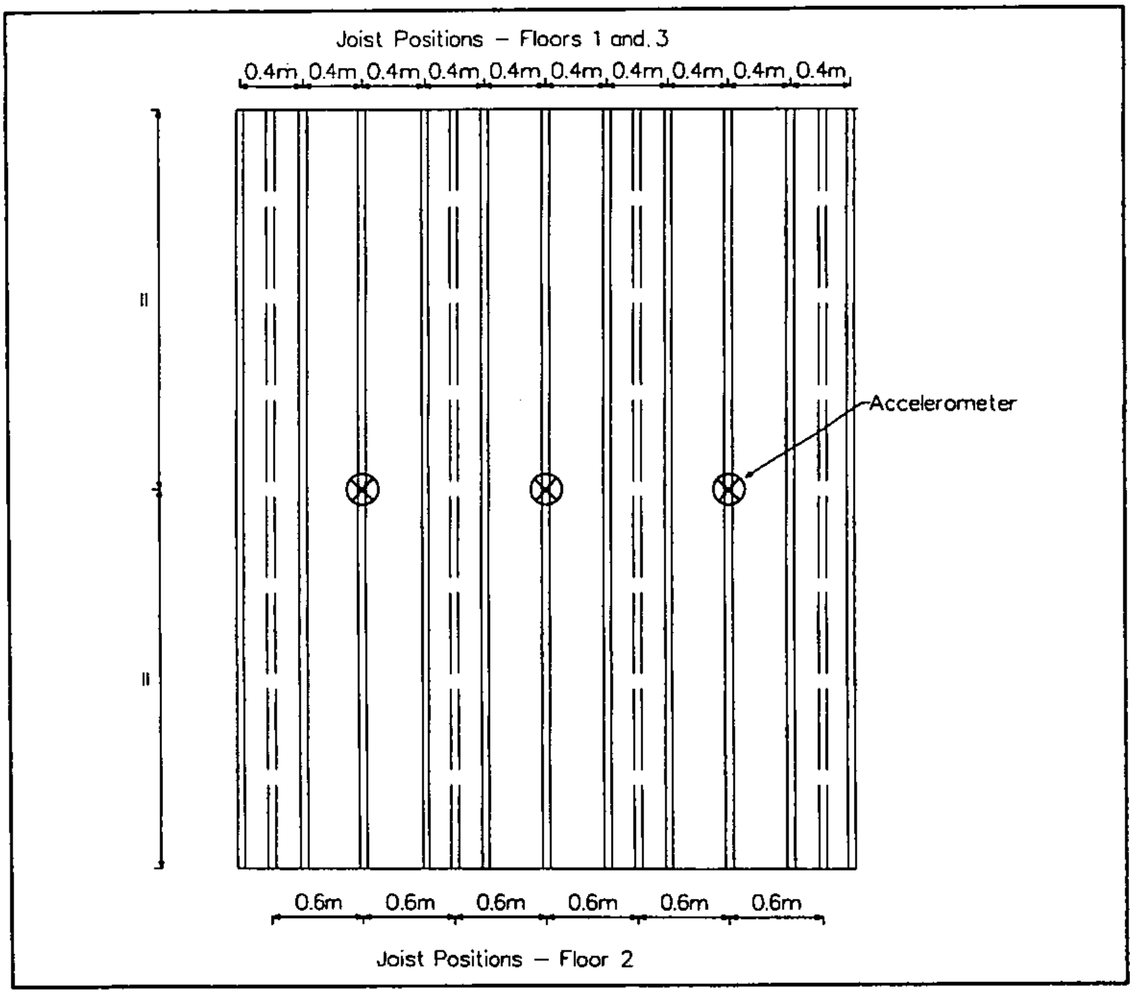

Figure 5: Location of accelerometers on the test floors

Two of the accelerometers were manufactured by CSIRO in Australia and the third by PCB Piezotronics. The CSIRO accelerometers had an output of approximately 0.43 g/volt with a +/-5 volt maximum output. Gravitational effects were not able to be balanced out which meant that 'clipping' of the signal occurred at +1.56g and -2.85g. The PCB accelerometer had an output of

1 g/volt and a maximum acceleration of 10g. Gravity forces did not influence the output of this accelerometer.

Data was captured using Dataq Instruments Inc CODAS data acquisition software. The scanning rate for data acquisition was 500 scans per second per channel.

3.2.3 Analysis procedure for recorded accelerations

The captured acceleration records for the three accelerometers were imported into the Microsoft Excel spreadsheet program. Generally, the length of excitation of the floor was approximately 2 seconds. Sometimes this period was a little longer but the acceleration levels were very small by this time. At a sampling rate of 500 Hz, about 1000 data points were logged for each channel on each test run. A Fast Fourier Transform (FFT) was conducted on a set of 4096 points to achieve an accuracy of 0.12 Hz in the resolution of the frequency domain plots. Because there were only 1000 actual data points available, zeros were added to the end of the record to facilitate the FFT analysis.

Modal frequencies were able to be taken off the FFT plots directly and the number less than 40 Hz was also recorded. The damping percentages were calculated using the bandwidth (half power) method on the first mode frequency. This method was suggested by Chui and Smith (1989) as "preferred if reliable estimates of damping values are required". In the method, the bandwidth is measured at $1/\sqrt{2}$ of the peak amplitude and divided by the sum of the two frequencies to determine the damping (see Figure 6).

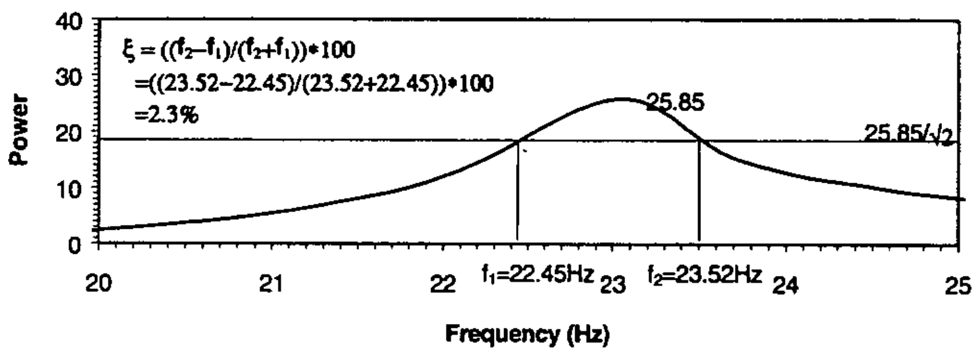

Figure 6: Bandwidth Method for Calculating the Damping

3.3 Experimental Summary

3.3.1 Floor number 1

The floor was set up so that it had clear spans of 4.8 m, 4.2 m and 3.6 m between supports. It was tested with no blocking, one row of blocking at mid span and two rows of blocking placed at approximately the one span points for the longest span. With two rows of blocking added, a plasterboard ceiling on timber battens was installed on the underside of the floor.

Static live loads were created by placing 16 kg concrete masonry blocks in an even distribution over the floor.

(a) Static Tests

For the static tests a load was applied at the centre of the floor in increments of approximately 200 N up to a maximum load of 2 kN, and then decrementally unloaded.

(b) Dynamic Testing

The dynamic loading phase was interspersed between the static load tests. The exact method of applying the dynamic excitation to the floor had not been determined at the start of the investigation and a number of methods were trialed. Initially, a punchbag weighing 9 kg was dropped 500 mm onto the floor centre point. The same bag was then dropped from 250 mm. The bag exhibited a clear bounce on impact, resulting in it providing a second impact which complicated the recorded behaviour of the floor. A soft bag was made up which contained 3.7 kg of lead shot. When dropped on the floor, the shot spread sideways within the confines of the bag and there was no observable rebound. Initially the bag was dropped from 1 metre but the height was reduced to 500 mm when it was found that the accelerations were too great for the accelerometers to record without over-ranging. Tests were also carried out using the heel drop of a 75 kg person and using a heel drop simulator.

The principle of operation of the heel drop simulator is that a weight on a guide is released and allowed to impact on the floor. A spring attached beneath the weight causes the weight to rebound. At the top of the rebound stroke, when the weight is stationary, it is arrested by a catch mechanism. Because the weight is arrested when stationary, the size of the second impact force due to the arrest is minimised.

It was found that the extra mass of the person carrying out the heel drop test was sufficient to influence the fundamental frequency of the floor and also the damping of the system and this method was therefore rejected as the primary excitation method. The heel drop simulator was found to introduce a significant amount of "noise" to the recorded traces because of the less than smooth action of the falling weight and catch mechanism and was also rejected as a primary excitation technique. The soft bag full of lead shot was chosen as the usual method for floor excitation during the test series.

With the floor initially set at a span of 4.8 m, the effect of clamping the supported ends to the top of the supporting wall was investigated. The first mode natural frequency of response was found not to change and the higher modes only changed slightly when the floor was clamped, so it was decided to always clamp for the dynamic tests. In this way it was also known that there was no vibration caused by joists not quite fully supported on the wall and it was more representative of field situations.

Generally, three bag drops were carried out for each variation in the floor setup to ensure that the results were repeatable.

The static and dynamic tests were undertaken with the clear span of the floor set at 4.8m, 4.2m and 3.6m. The summary of setups for Floor 1, along with recorded frequencies and damping, is presented in Table 2. Static tests were interspersed with the dynamic tests as the setup conditions changed.

Table 2: Test Conditions and Results for Floor 1

Dynamic Test No.s	Floor Setup Conditions	Excitation Method*	Fundamental Frequencies (Hz)				Damping (% crit)
			Mode 1	Mode 2	Mode 3	Mode 4	
4.8 m span							
1-3	1 row blocking, not clamped	2	11.6	15.3	29.5	NI*	2.5
6-8	1 row blocking, clamped	1	12.2	16.5	31.0	55.0	2.4
9-10	1 row blocking, not clamped	1	12.1	16.0	30.5	55.0	2.2
11	1 row blocking, clamped	4	11.7	16.6	29.4	31.7	3.7
14-16	1 row blocking, not clamped	3	11.9	16.5	30.3	NI	3.0
17-19	1 row blocking, not clamped	1	12.4	17.1	31.7	56.6	2.1
20	1 row blocking, clamped, outside joists propped	3	13.1	26.0	NI	NI	12.2
21-22	1 row blocking, clamped, outside joists propped	1	13.2	26.8	50.0	NI	2.3
50-52	No blocking , clamped	1	12.5	16.3	23.8	39.0	1.3
53-55	2 rows of blocking, clamped	1	12.3	18.3	41.5	NI	1.5
56-58	2 rows of blocking, clamped, outside joists propped	1	13.5	23.1	35.5	NI	1.9
72-74	2 rows of blocking, not clamped, plaster ceiling	1	11.5	21.4	42.1	45.0	2.3
75-77	2 rows of blocking, clamped, plaster ceiling	1	12.0	22.4	42.3	45.4	2.0
78-81	2 rows of blocking, clamped, plaster ceiling, outside joists propped	1	15.0	34.6	56.2	NI	2.2
99-101	2 rows of blocking, clamped, plaster ceiling, 0.15 kPa static live load added	1	10.2	18.6	38.5	NI	2.3
102-104	2 rows of blocking, clamped, plaster ceiling, outside joists propped, 0.15 kPa static live load added	1	12.8	30.7	47.1	NI	1.9
105-107	2 rows of blocking, clamped, plaster ceiling, outside joists propped, 0.15 kPa static live load added, 4 people added	1	14.7	34.7	55.5	NI	6.5
4.2 m span							
23-25	1 row blocking, 4.2m span, not clamped	1	15.3	20.0	35.5	61.5	2.2
26-28	1 row blocking, 4.2m span, clamped	1	15.5	20.9	36.3	NI	2.0
29-31	1 row blocking , 4.2m span, clamped, outside joists propped	1	16.5	30.0	NI	NI	1.8

Dynamic Test No.s	Floor Setup Conditions	Excitation Method*	Fundamental Frequencies (Hz) Mode 1	Mode 2	Mode 3	Mode 4	Damping (% crit)
47-49	No blocking, clamped	1	16.1	21.0	29.7	43.0	1.4
59-61	2 rows of blocking, clamped	1	15.5	22.3	45.0	NI	1.3
62-64	2 rows of blocking, clamped, outside joists propped	1	16.8	37.4	NI	NI	1.5
82-84	2 rows of blocking, clamped, plaster ceiling	1	14.8	26.2	41.4	46.1	2.0
85-87	2 rows of blocking, clamped, plaster ceiling, overhanging ends propped	1	15.0	26.8	41.9	46.7	1.9
88-90	2 rows of blocking, clamped, plaster ceiling, overhanging ends propped, outside joists propped	1	16.9	34.7	53.2	NI	2.4
3.6m span							
32-34	1 row blocking, not clamped	1	18.8	26.0	41.4	65.7	2.3
35-37	1 row blocking, clamped	1	19.0	26.5	43.1	69.0	3.2
38-40	1 row blocking, clamped, outside joists propped	1	19.4	31.3	40.4	48.0	3.9
41-43	1 row blocking, clamped, overhanging ends propped	1	19.8	26.5	43.1	93.0	4.0
44-46	No blocking, clamped, no end props	1	20.1	26.5	36.3	50.0	4.0
66-68	2 rows of blocking, clamped, overhanging ends propped	1	20.5	28.3	50.9	80.5	7.1
69-71	2 rows of blocking, clamped, overhanging ends propped, outside joists propped	1	21.2	42.3	NI	NI	2.5
91-93	2 rows of blocking, clamped, plaster ceiling, overhanging ends propped	1	19.0	32.7	49.6	NI	3.7
94-96	2 rows of blocking, clamped, plaster ceiling, overhanging ends propped, outside joists propped	1	20.8	40.0	55.5	NI	3.2

* Key: 1 = Soft bag of lead shot (3.7 kg) from 500 mm
2 = Punchbag (9 kg) from 500 mm
3 = Heeldrop from 75 kg person
4 = Simulated heeldrop
NI= Not identified

(c) Floor Weight

The floor weight with two rows of blocking present was 6.59 kN (672 kg) or 0.312 kPa. The addition of ceiling battens and ceiling lining increased the weight to 8.32 kN (848 kg) or 0.394 kPa.

3.3.2 Floor number 2

The floor was set up so that it had a clear spans of 4.8 m, 4.0 m and 3.2 m between supports.

(a) Static Tests

The static tests were conducted in the same manner as described in section 3.3.1 for Floor number 1.

(b) Dynamic Testing

The dynamic loading phase was interspersed between the static load tests. The soft bag of lead shot was used to apply all the dynamic excitation on this floor. Generally, three drops were done for each variation in the floor setup to ensure that the results were repeatable. Floor 2 was always clamped at the supports for the dynamic testing.

The summary of setups for Floor 2, along with recorded frequencies and damping, is presented in Table 3.

Table 3: Test Conditions and Results for Floor 2

Dynamic Test No.s	Floor Setup Conditions	Excitation Method*	Fundamental Frequencies (Hz) Mode 1	Mode 2	Mode 3	Mode 4	Damping (% crit)
4.8m span							
1-3	1 row of blocking,	1	11.4	16.9	33.4	NI	2.0
4-6	1 row of blocking, outside joists propped	1	12.7	29.6	59.3	NI	2.1
22-24	1 row of blocking, floor glued to joists	1	11.7	17.4	34.9	60.8	2.2
25-27	1 row of blocking, floor glued to joists, outside joists propped	1	13.2	29.7	35.4	60.6	2.1
37-39	1 row of blocking, floor glued to joists, 0.15 kPa static live load	1	9.7	14.8	31.1	NI	2.4
40-42	1 row of blocking, floor glued to joists, 0.15 kPa static live load, outside joists propped	1	11.0	25.6	NI	NI	2.2
43-45	1 row of blocking, floor glued to joists, 0.15 kPa static live load, carpet and underlay	1	9.3	13.2	38.4	NI	2.7
46-48	1 row of blocking, floor glued to joists, 0.15 kPa static live load, carpet and underlay, outside joists propped	1	10.3	38.7	NI	NI	2.5
49-51	1 row of blocking, floor glued to joists, 0.15 kPa static live load, carpet and underlay, 4 people, outside joists propped	1	10.5	39.7	NI	NI	10.8

Dynamic Test No.s	Floor Setup Conditions	Excitation Method*	Fundamental Frequencies (Hz)				Damping (% crit)
			Mode 1	Mode 2	Mode 3	Mode 4	
52-54	1 row of blocking, floor glued to joists, 0.15 kPa static live load, carpet and underlay, 4 people	1	9.2	13.4	39.4	NI	10.0
55-57	1 row of blocking, floor glued to joists, 0.15 kPa static live load, 4 people, outside joists propped	1	NI	NI	NI	NI	NI
58-60	1 row of blocking, floor glued to joists, 0.15 kPa static live load, 4 people	1	14.6	NI	NI	NI	2.0
4.0m span							
7-9	1 row blocking, floor not glued	1	15.4	22.6	39.9	63.7	2.0
10-12	1 row blocking, floor not glued, outside joists propped	1	17.1	37.4	65.5	NI	2.3
34-36	1 row of blocking, floor glued to joists	1	16.5	24.0	42.3	67.8	1.9
28-30	1 row of blocking, floor glued to joists, outside joists propped	1	18.2	39.0	70.0	NI	2.7
31-33	1 row of blocking, floor glued to joists, outside joists propped, overhanging ends propped	1	19.0	39.4	NI	NI	4.6
3.2m span							
13-15	1 row blocking,	1	21.4	31.1	48.5	NI	2.4
16-18	1 row blocking, outside joists propped	1	23.2	41.5	45.6	49.8	2.3
19-21	1 row blocking, outside joists propped, overhanging ends propped	1	25.8	43.0	47.7	NI	3.2

* Key: 1 = Soft bag of lead shot (3.7 kg) from 500 mm

NI= Not identified

At the completion of the tests on the floor spanning between the two supports, the carpet, underlay and live load were removed and the supporting walls were rearranged so that a cantilever section of floor was created. The clear span of the floor between supports was 3.35m and the cantilever section measured 1.5m (1.55m from the centre of the support). The lead shot was dropped at two locations as shown in Figure 7 and the accelerations were recorded at two locations. Finally, accelerations were recorded while a person walked about on the floor.

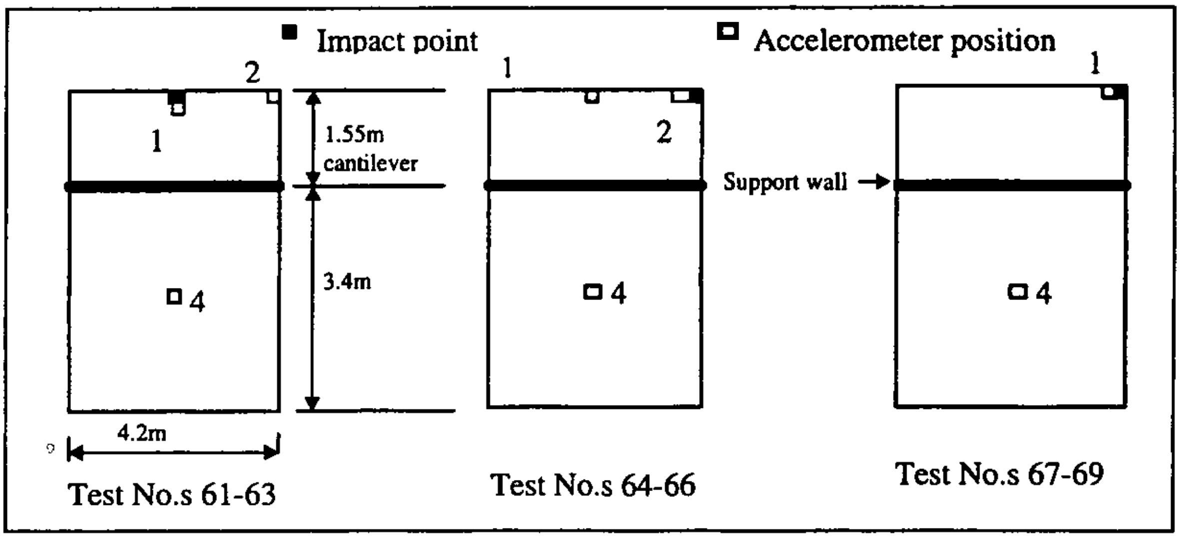

Figure 7: Locations of Drop Points and Accelerometers on Floor 2 Cantilever Tests

Table 4: Cantilever Tests on Floor 2

Dynamic Test No.s	Floor Setup Conditions	Excitation Method*	Fundamental Frequencies (Hz) Mode 1	Mode 2	Mode 3	Mode 4	Damping (% crit)
61-63	1.5m cantilever	1	17.1	26.4	29.0	29.9	1.3
64-66	1.5m cantilever	1	16.8	18.0	29.3	41.0	NI
67-69	1.5m cantilever	1	16.7	18.4	29.4	41.2	NI
70	1.5m cantilever	Walking	Frequencies between 17 & 20 Hz				

* Key: 1 = Soft bag of lead shot (3.7 kg) from 500 mm
NI= Not identified

(c) Floor Weight

The floor weight with one row of blocking present was 5.04 kN (514 kg) or 0.25 kPa.

3.3.3 Floor number 3

(a) Static Tests

The static tests were conducted in the same manner as described in section 3.3.1 for Floor 1.

(b) Dynamic Testing

The dynamic loading phase was interspersed between the static load tests. Three methods were used to apply the dynamic loading. For each floor setup condition the soft bag of lead shot was dropped twice and the heel drop and heel drop simulator were used once each. Floor 3 was always clamped at the supports during the dynamic tests.

The static and dynamic tests were undertaken with the clear span of the floor set at 4.0m, 3.4m and 2.8m. The summary of setups for Floor 3, along with recorded frequencies and damping, is presented in Table 5.

Table 5: Test Conditions and Results for Floor 3

Dynamic Test No.s	Floor Boundary Conditions	Excitation Method*	Fundamental Frequencies (Hz) Mode 1	Mode 2	Mode 3	Mode 4	Damping (% crit)
4.0m span							
29-30	No blocking	1	11.9	16.0	25.7	46.3	2.0
31		4	11.2	15.0	26.0	NI	3.0
32		3	10.6	15.3	25.8	NI	18.0
1-2	Mid span strongback	1	11.6	17.1	30.1	44.1	2.1
3		4	11.4	15.0	18.2	24.0	5.7
4		3	11.0	19.6	30.4	44.0	17
33-34	1 row of blocking	1	11.7	16.3	31.3	NI	2.2
35		4	11.0	15.1	29.7	NI	3.3
36		3	10.8	16.8	31.6	NI	16.7
37-38	1 row of blocking, plaster ceiling	1	12.2	21.8	39.7	NI	3.1
39		4	11.7	20.4	23.5	38.5	3.5
40		3	11.3	21.4	30.0	38.3	10.4
61-62	1 row of blocking, plaster ceiling, carpet and 0.15 kPa static live load	1	9.8	16.0	35.9	NI	2.9
63		4	9.4	15.0	20.5	25.3	4.2
64		3	9.6	14.6	27.0	NI	11.0
65-66	1 row of blocking, plaster ceiling, carpet and 0.6 kPa static live load	1	7.5	12.2	46.9	NI	3.3
67		4	7.3	11.6	39.5	43.0	2.9
68		3	7.0	11.5	23.0	NI	5.7
3.4m span							
25-26	No blocking	1	15.3	20.7	31.8	51.0	1.5
27		4	14.3	NI	NI	NI	3.9
28		3	14.6	20.0	30.5	46.0	14.0
5-6	Mid span strongback, clamped	1	15.3	25.0	51.5	NI*	1.5
7		4	14.5	24.0	32.0	34.0	8.2
8		3	14.9	25.1	31.6	35.9	11.3
45-46	1 row of blocking, plaster ceiling	1	14.7	25.0	43.7	NI	2.2
47		4	13.8	23.0	26.5	35.7	4.9
48		3	14.0	24.2	43.0	NI	9.2

Dynamic Test No.s	Floor Boundary Conditions	Excitation Method*	Fundamental Frequencies (Hz) Mode 1	Mode 2	Mode 3	Mode 4	Damping (% crit)
69-70		1	8.9	9.7	13.4	45.4	2.9
71	1 row of blocking, plaster ceiling, carpet and 0.6 kPa static live load	4	8.7	9.3	12.3	39.6	4.0
72		3	8.2	12.0	21.0	42.3	12.2
9-10		1	20.5	30.7	60.0	NI	3.4
11	Mid span strongback, 2.8m span, clamped	4	19.5	NI	NI	NI	4.4
12		3	19.6	30.4	60.5	NI	10.2
13-14		1	23.0	30.8	37.0	60.0	2.7
15	Mid span strongback, 2.8m span, clamped, overhanging ends propped	4	22.8	NI	NI	NI	2.8
16		3	21.6	26.0	29.6	35.8	13.9
2.8m span							
17-18		1	19.1	21.2	25.5	30.0	2.3
19	No blocking	4	18.5	21.7	25.0	26.8	3.6
20		3	18.7	24.0	28.4	35.4	12.6
21-22		1	21.7	23.9	25.5	29.6	1.8
23	No blocking, overhanging ends propped	4	21.8	25.0	28.3	30.5	6.8
24		3	21.1	25.0	29.2	35.4	15.2
53-54		1	18.9	30.8	37.7	NI	7.4
55	1 row of blocking, plaster ceiling, overhanging joists propped	4	18.2	23.0	25.9	30.5	5.8
56		3					
73-74		1	12.1	15.7	45.7	NI	4.1
75	1 row of blocking, plaster ceiling, carpet and 0.6 kPa static live load, overhanging joists propped	4	11.5	14.8	20.5	38.5	5.2
76		3	11.3	14.7	21.3	45.8	10.4

* Key: 1 = Soft bag of lead shot (3.7 kg) from 500 mm
3 = Heeldrop from 75 kg person
4 = Simulated heeldrop
NI= Not identified

(c) Floor weights

The floor weight with no blocking present was 4.62 kN (471 kg) or 0.263 kPa. The addition of blocking, ceiling battens and 9.5 mm plasterboard ceiling lining increased the weight to 5.74 kN (585 kg) or 0.326 kPa.

4. EXPERIMENTAL RESULTS

4.1 Static Deflection Behaviour and Load Distribution

The method of determining the deflection distribution across the floor was varied through the test programme. All floors were constructed so that they were essentially symmetric about the centre joist. Because of this, when a deflection gauge was not present on the opposite side of the centre joist from the measured deflection point, it was assumed that the two would be the same. For joists between the recording points, no attempt was made to estimate the deflection. Instead, a straight line was drawn between the measured values.

According to various sources, under a point load, the floor is expected to deflect less than a specified upper limit in order to have a satisfactory dynamic performance. Various sources suggest different limits and these are presented in Table 6. It should be noted that satisfaction of these criteria will not always guarantee a satisfactory performance from a floor.

Table 6: Prescribed Maximum Deflections under 1 kN Point Load

Source	Specified Deflection Upper Limit (mm)
NZS 4203 Table C2.4.1(1992)	1.0
European Committee for Standardisation EC5 (1994)	1.5
King (1996)	1.5
AS 3623 (1993)	2.0

4.1.1 Floor 1 static deflection tests

The floor static deflection test results are summarised in Figures 8 to 11. In Table 8 the "no blocking", "one row of blocking" and the "two rows of blocking" cases are erroneous in that the deflections of the joists at 400 mm and 800 mm are expected to be less than the linearly interpolated values plotted. The slopes would have been greater than those for the case with the ceiling.

From the plots it is clear that the addition of a ceiling has the greatest influence on the load sharing capability of the floor. The inclusion of either one or two rows of solid blocking has a minor effect on the ability to share load and two rows appears to provide no better load sharing than a single row. Finite element modelling of the floor confirmed however, that the addition of a ceiling without blocking did little to spread the load (see section 4.4).

For each configuration, the mid span deflection versus the floor span has been plotted in Table 11. Also plotted on this graph is the maximum span for 200 x 50 joists at 400 centres from NZS 3604. The graph shows that the inclusion of blocking and then a ceiling causes deflections less than the maximum allowable deflection from Table 6 (1 mm) at the maximum allowable NZS 3604 span (3.8m). Even with no blocking present the deflection is only marginally outside the 1 mm limit and would be considered acceptable by all Table 6 sources except NZS 4203.

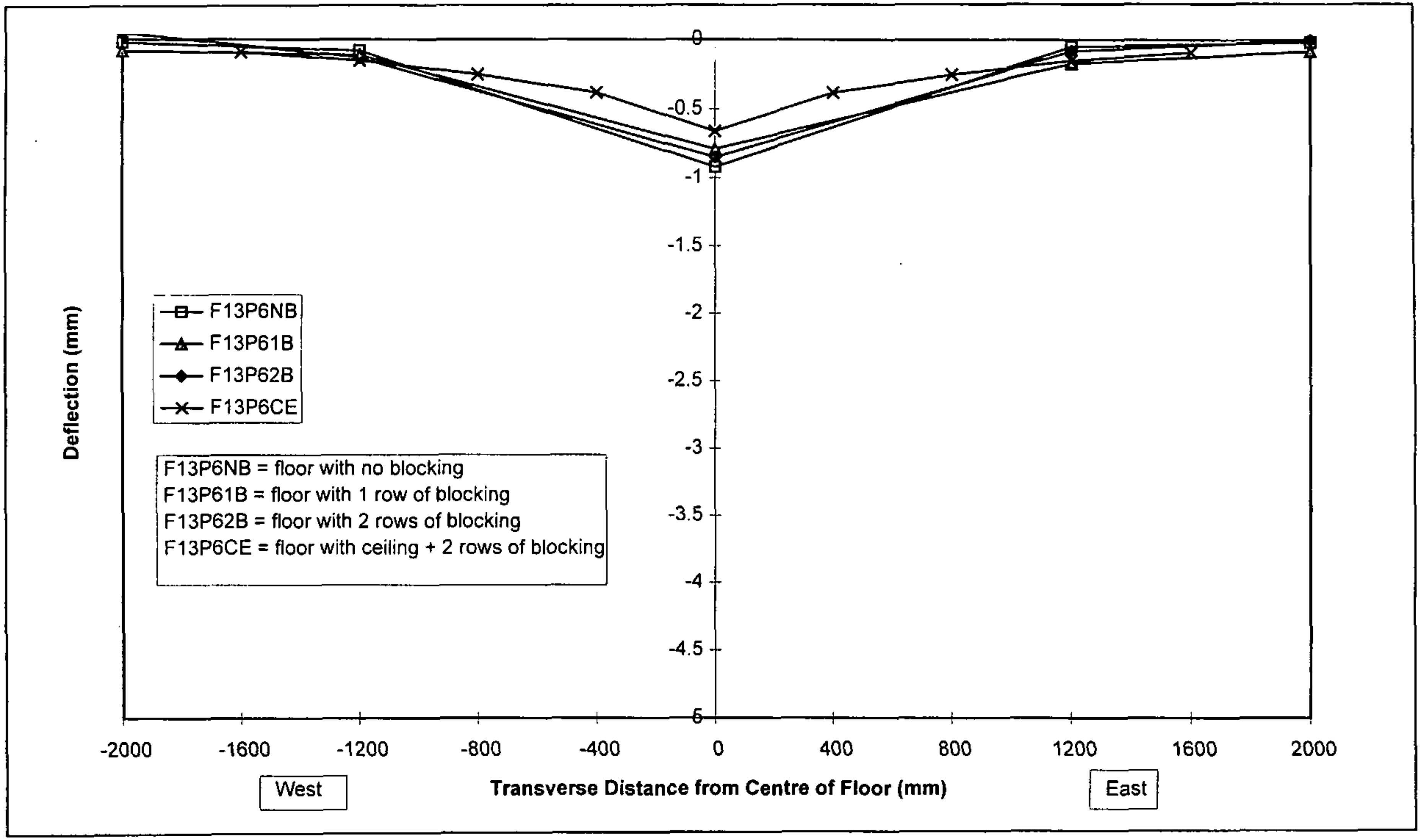

Figure 8: Floor 1 Deflection Profile under 1 kN Point Load - 3.6m Span

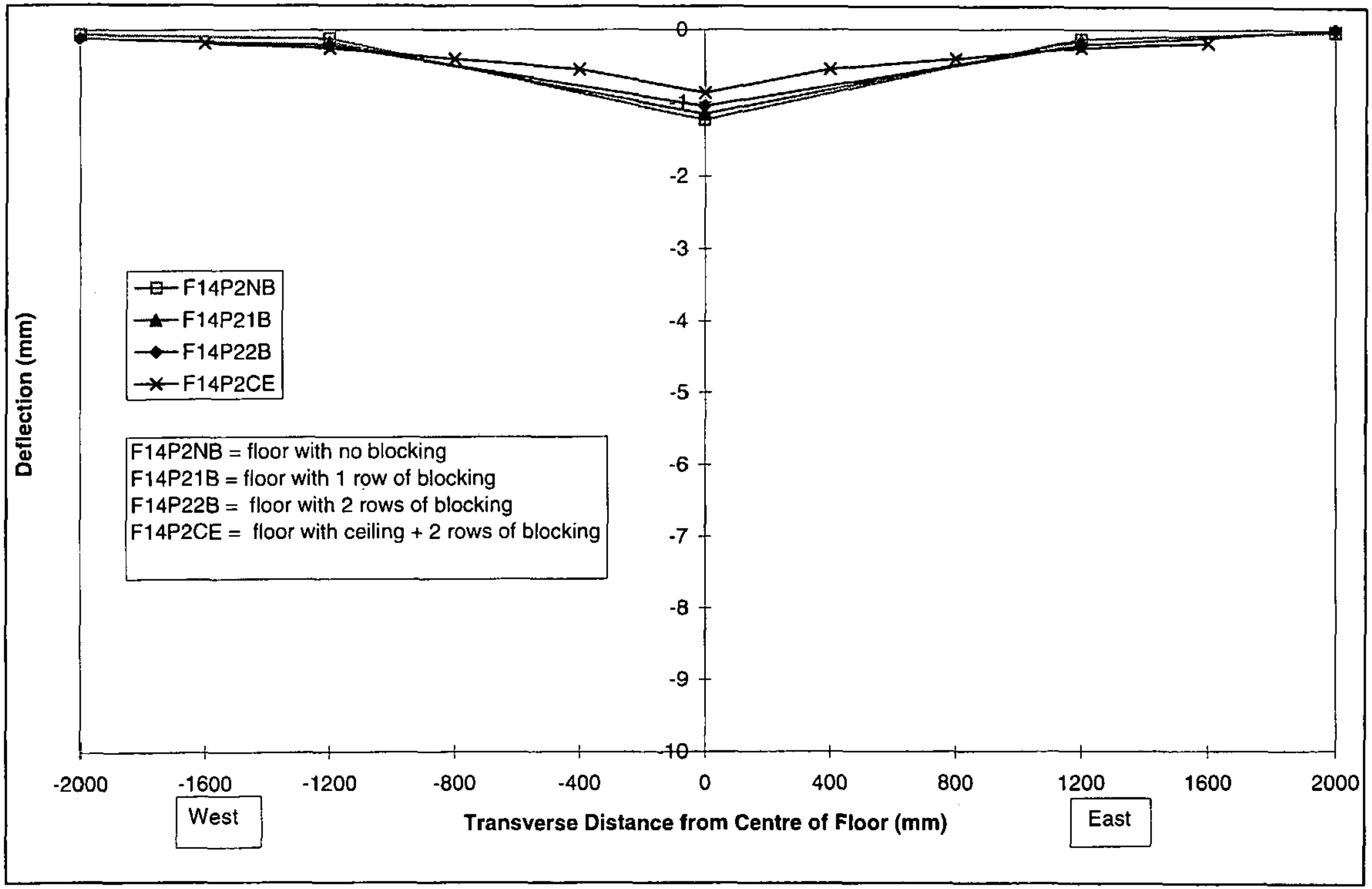

Figure 9: Floor 1 Deflection Profile under 1 kN Point Load - 4.2m Span

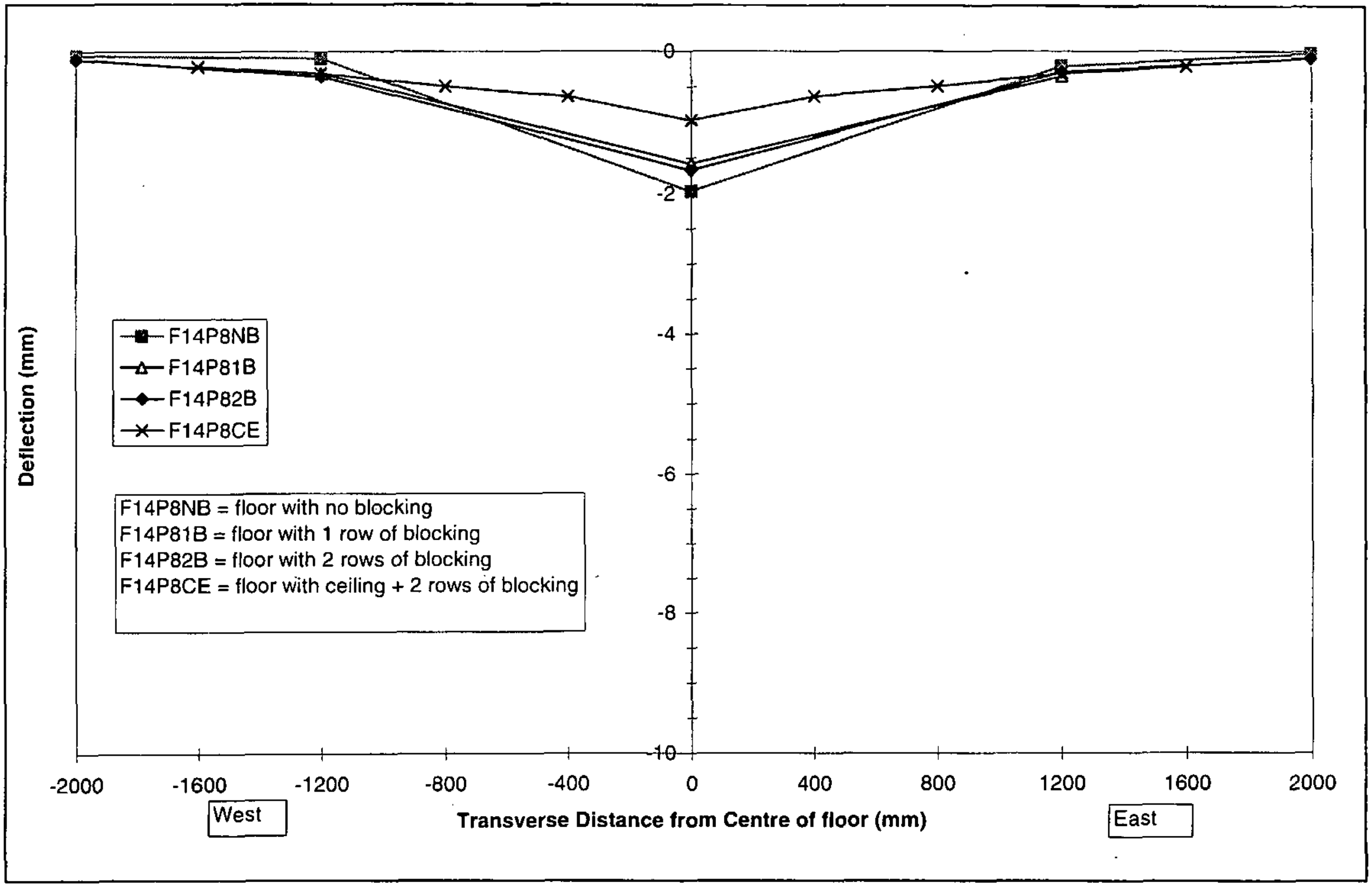

Figure 10: Floor 1 Deflection Profile under 1 kN Point Load - 4.8m Span

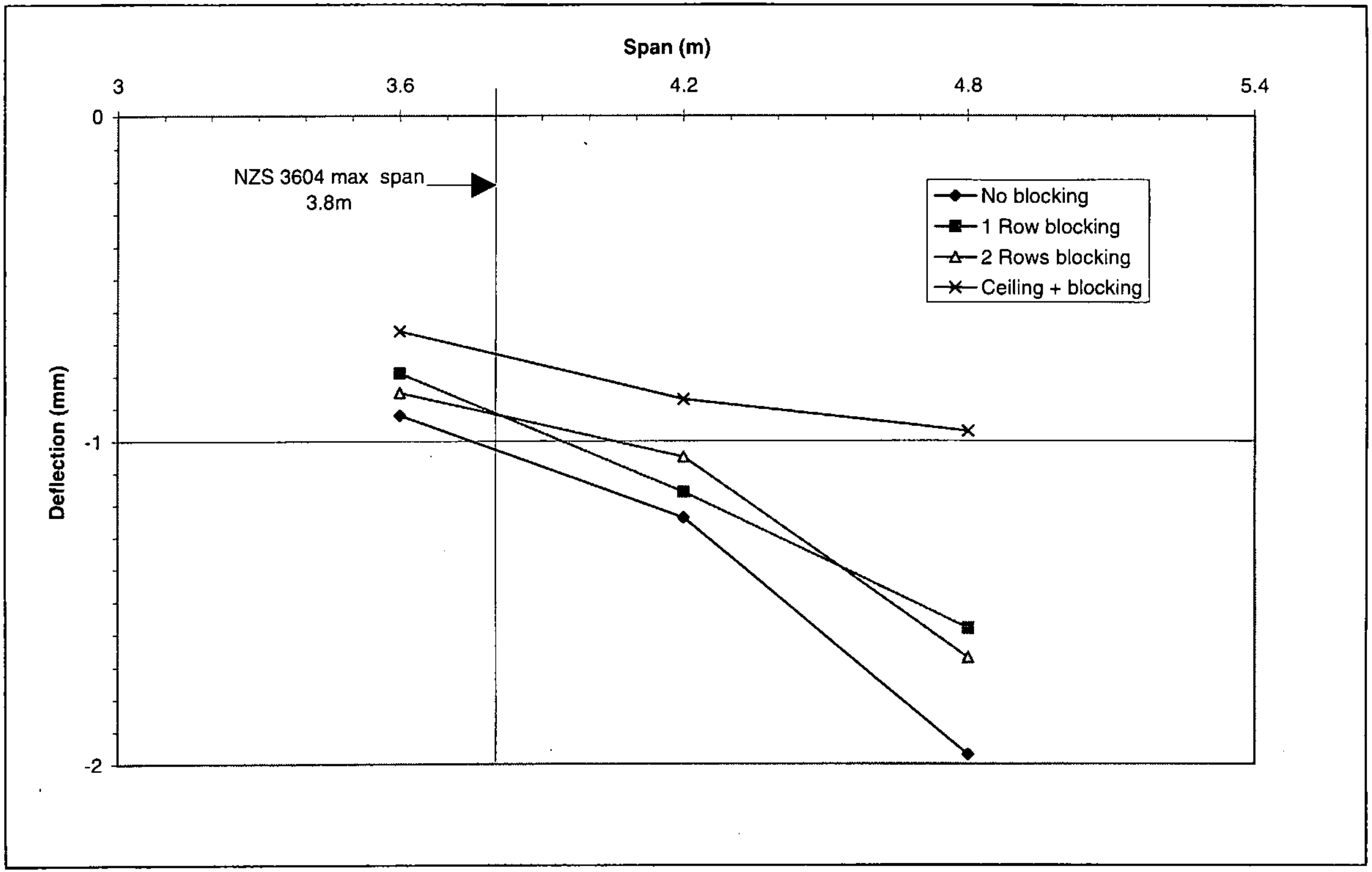

Figure 11: Deflection versus Span for the Various Configurations of Floor 1

4.1.2 Floor 2 static deflection tests

Static deflections were recorded under the point load on Floor 2 only in the cases of nailed flooring and nailed and glued flooring (Figure 12 and Figure 13). From Figure 12 and Figure 13 it appears that the gluing has significantly increased the stiffness of the floor, as evidenced by the smaller joist deflections after gluing. There were no static deflection measurements made on the 3.2m span floor after gluing.

As with Floor 1, the deflection versus span relationship is plotted in Figure 14 for both cases. By interpolation between the experimental results it can be seen that in the unglued case the deflection exceeds 1 mm at approximately the 3.6m span. While there is no result for the glued 3.2m span it is reasonable to assume that the trend would be similar to the unglued case. This would indicate that about a 200 mm increase in span over the unglued case (to 3.8m) would be possible in the glued case before the 1 mm deflection was exceeded.

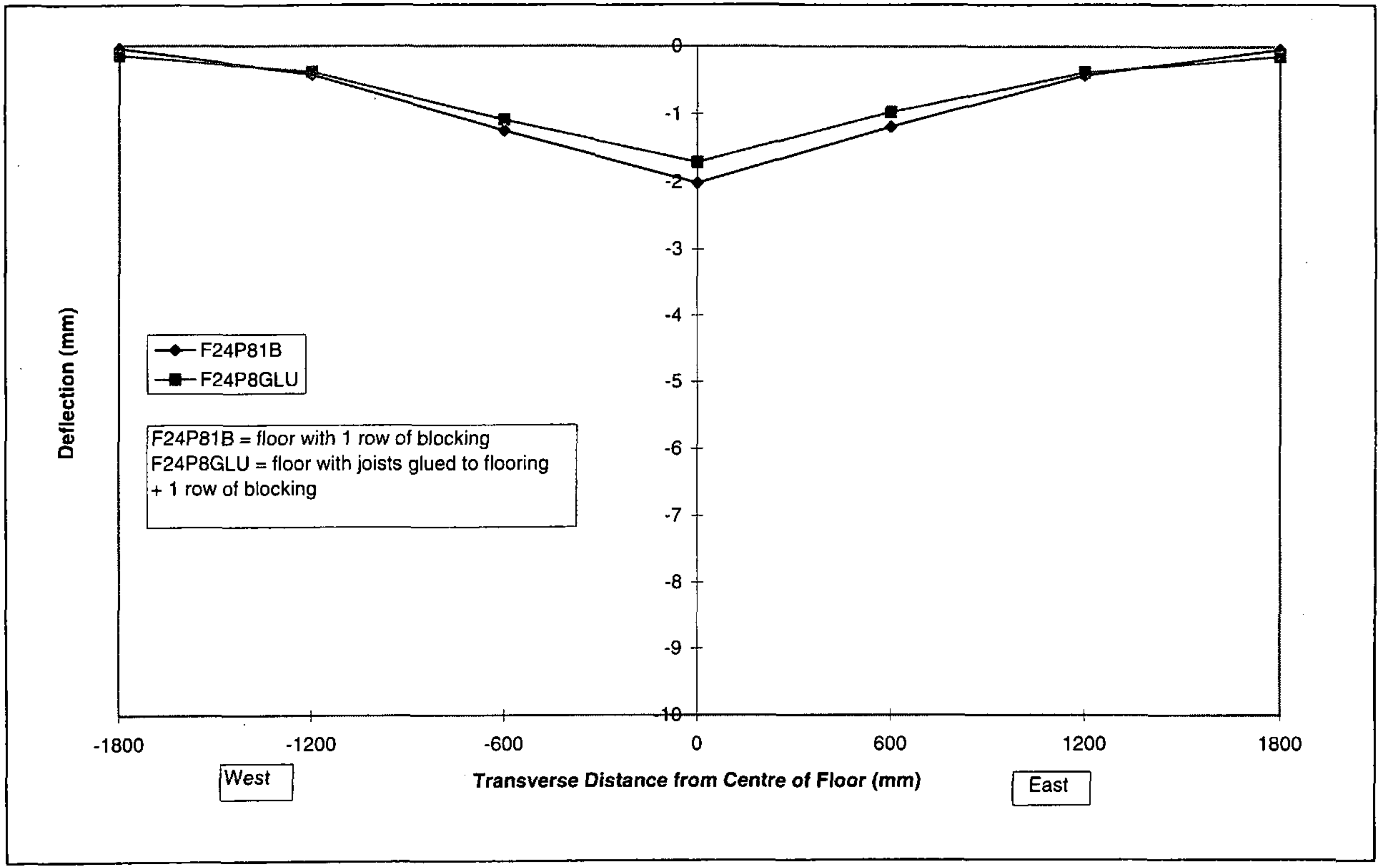

Figure 12: Deflection of Floor 2 under 1 kN Point Load - 4.8m span

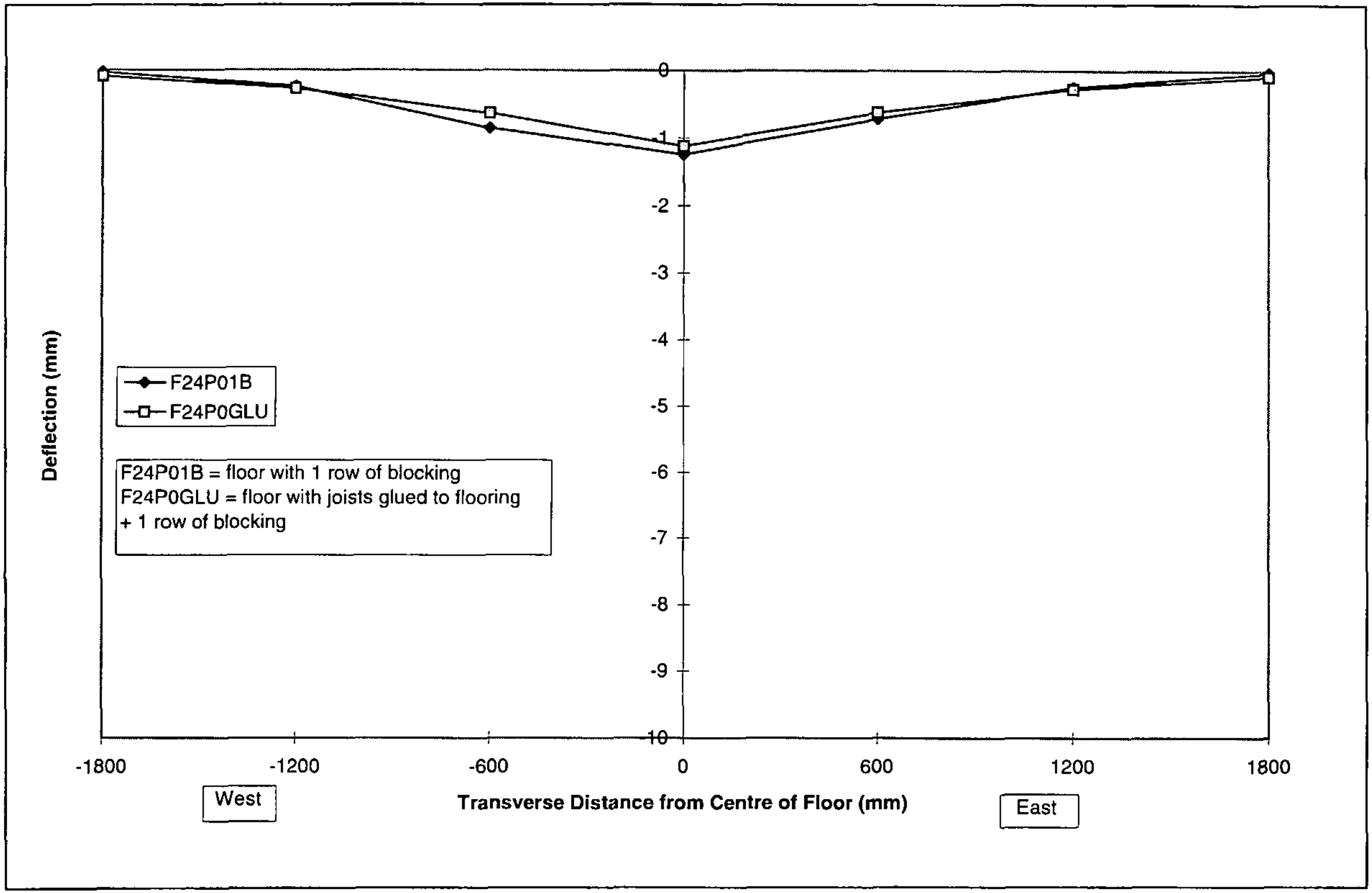

Figure 13: Deflection of Floor 2 under 1 kN Point Load - 4.0m span

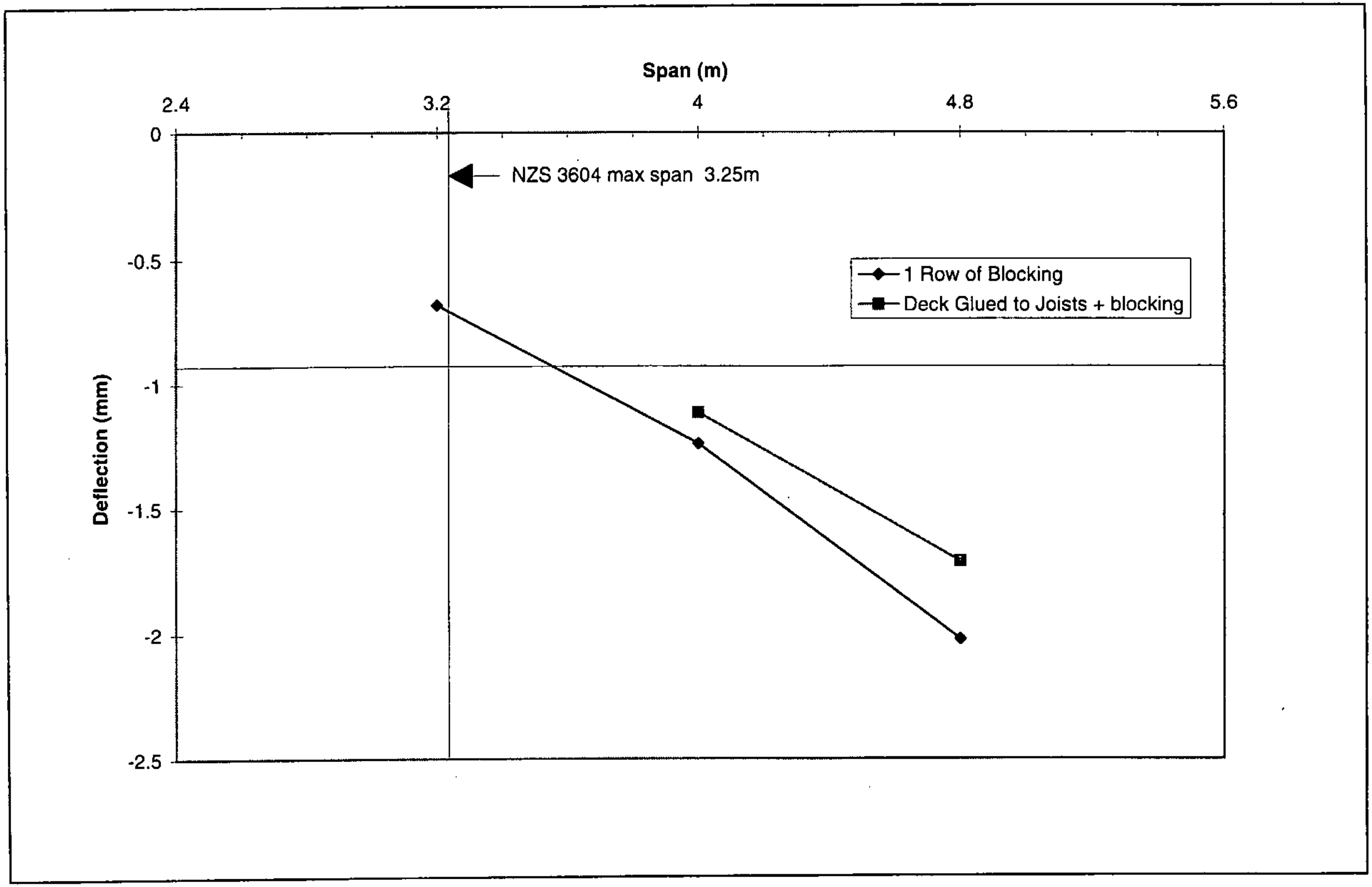

Figure 14: Deflection versus Span for the Various Configurations of Floor 2

4.1.3 Floor 3 static deflection tests

A complete set of static deflection tests was undertaken on Floor 3 at the 4.0m span position. At the 2.8m and 3.4m spans a comparison was made between the floor with the strongback in position and the unblocked floor. Plots of the deflections recorded under a 1 kN point load at 4.0m and 2.8m spans are presented in Figure 15 and Figure 16. Clearly, the strongback serves to spread the load to the adjacent joists more efficiently than the flooring alone. The addition of one row of blocking improves the performance over the unblocked case but, as expected, it is not as efficient as the continuous strongback.

As with Floor 1, the addition of the ceiling battens and ceiling lining caused a significant spread of load to the outer joists, better than the strongback case. The apparent large deflection of the outermost joists does not follow the expected trend, based on the other points in Figure 15. This may have been due to an observation error in the gauge reading.

Centre joist deflections under the 1 kN point load versus span are plotted in Figure 17. With the strongback installed, the suggested 1 mm deflection limit is reached at approximately 3m span. While there is only one point at the 4m span for the ceiling case, if it follows the same trend as the strongback case it would be expected to reach 1 mm deflection at a span of 3m also. Extrapolating back for the case with no blocking, the 1 mm deflection is reached at approximately 2.7m.

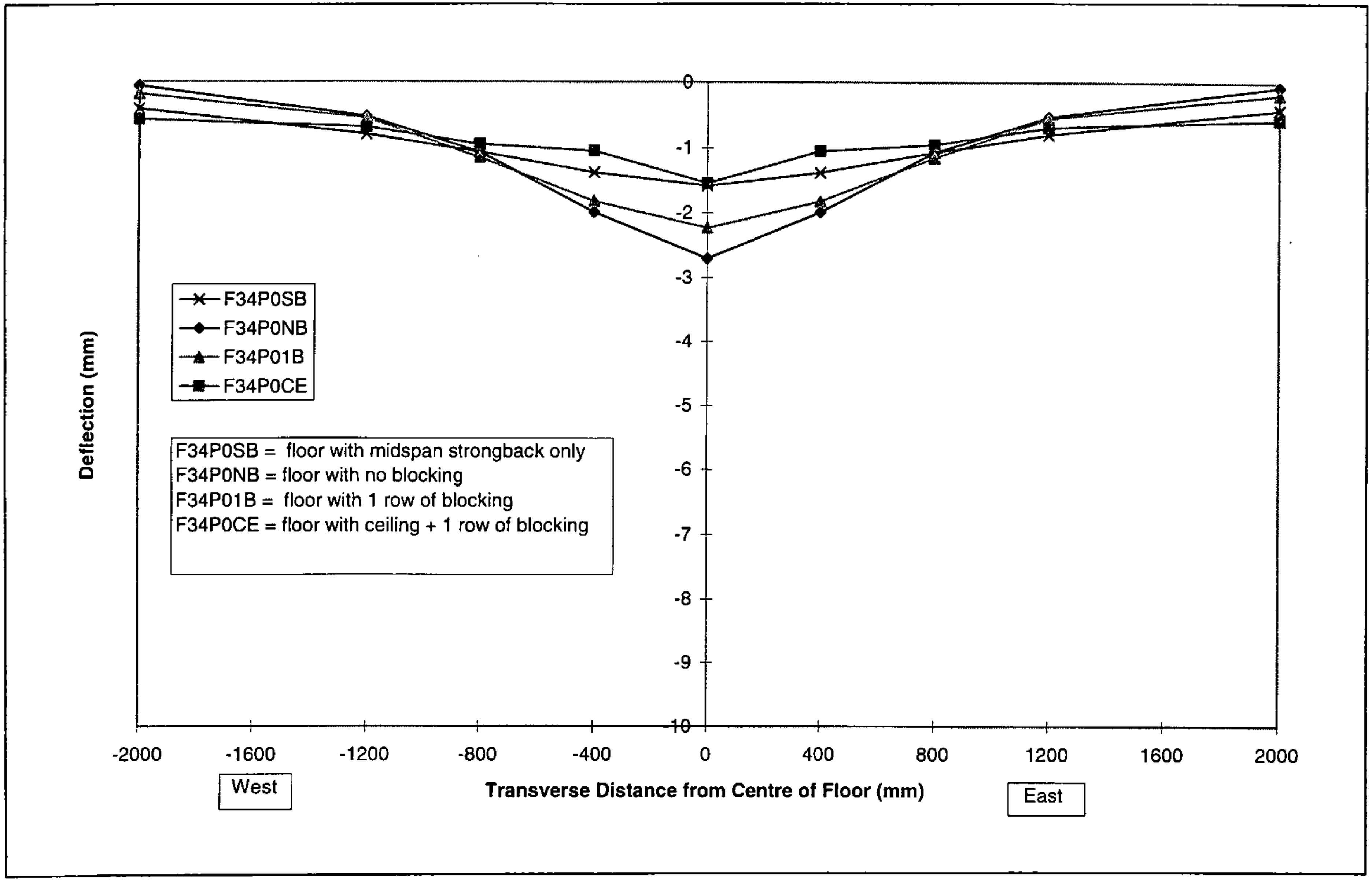

Figure 15: Deflection of Floor 3 under 1 kN Point Load - 4.0m span

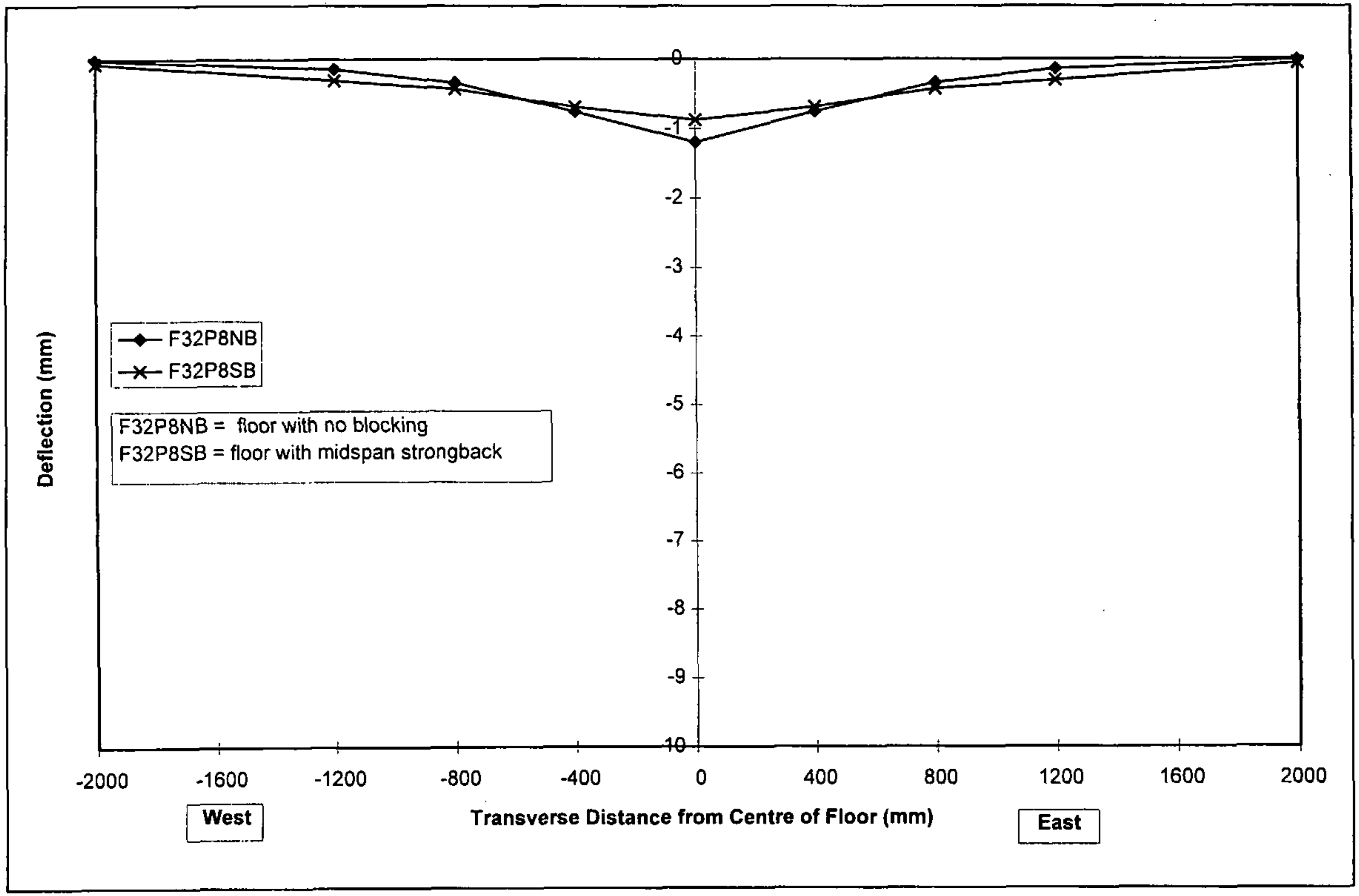

Figure 16: Deflection of Floor 3 under 1 kN Point Load - 2.8m span

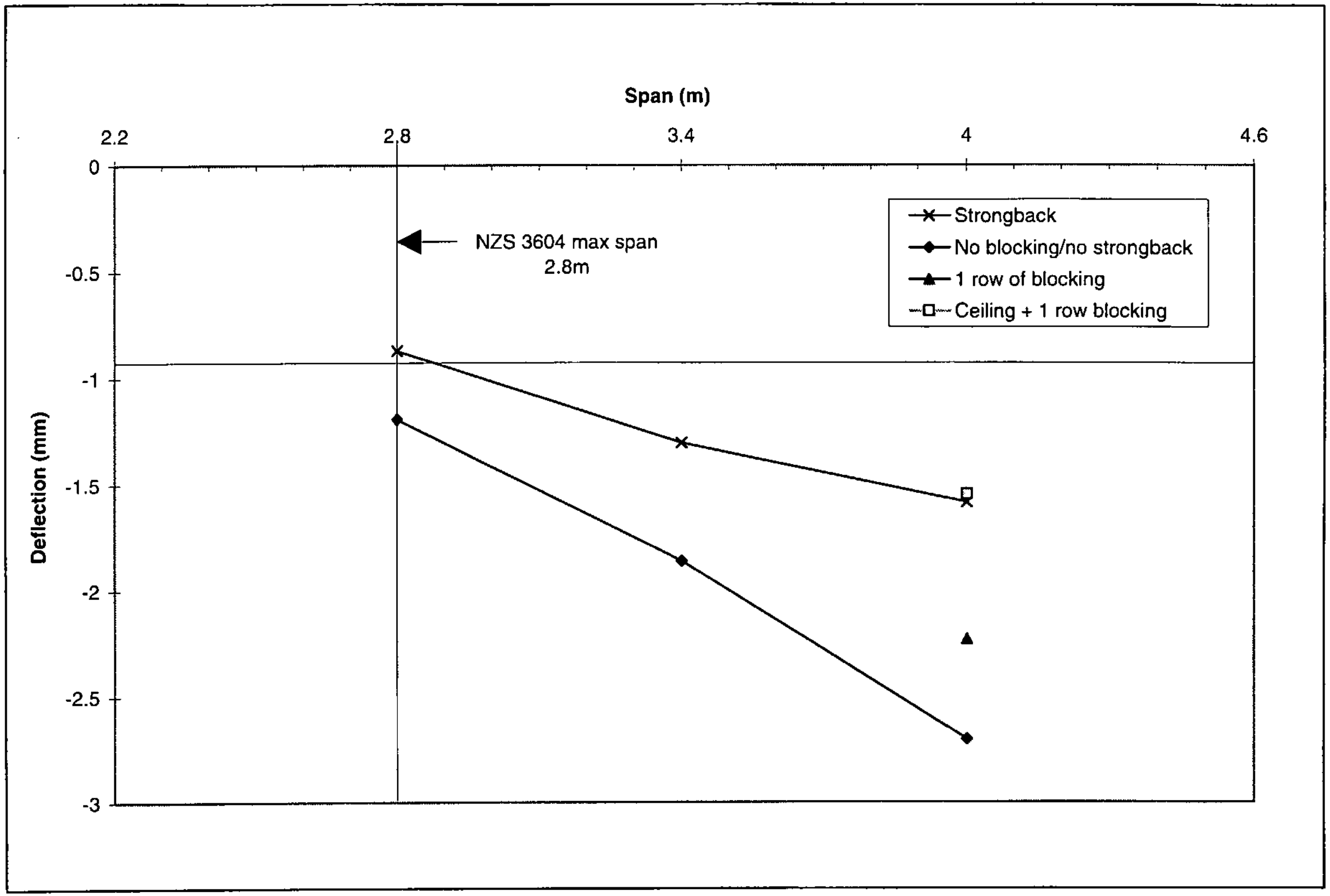

Figure 17: Deflection versus Span for the Various Configurations of Floor 3

4.1.4 Discussion of static deflection behaviour

The static test results indicate that if a deflection limitation of 1 mm under a 1 kN static load was used, then the maximum spans in NZS 3604 (1992) could be increased, provided that they were not already limited by either live load deflection or strength. A comparison of the NZS 3604 maximum deflections and those suggested using the 1 mm deflection limitation for nominal 200 mm x 50 mm joists is presented in Table 7.

Table 7: Maximum Spans based on Static Deflection (nominal 200 x 50 joists)

Joist spacing	NZS 3604 Maximum Span (m)	Suggested Maximum Span based on 1 mm deflection limit under 1 kN point load (m)
400	3.8	3.9
600	3.25	3.6

From Table 7, it is clear that the relationship between the NZS 3604 maximums and the maximums from the experimental results is not constant. Because of this and the limited number of experimental results, it is not possible to propose any change from the existing spans.

It is suggested that controlling floor dynamic behaviour is best achieved by the use of rationally based dynamic criteria rather than static deflection limits.

4.2 Comparison of Theoretical and Experimental Static Behaviour

The prediction of the deflection of the floor under the 1 kN static point load is a complicated matter. The joists cannot be considered as individual elements because that would mean that the central joist would be expected to support the load with no contribution from the adjacent joists, which is known to be incorrect. Further, the contributions of the decking, blocking and ceiling to the stiffness of the central joist are variable, depending on their connection details. That is, while they assist the central joist via their connection to it, the transverse flexibility of the floor means that the adjacent joists deflect less than the central joist.

If it is assumed that there is no composite action between the joists and the flooring, the second moment of inertia of the joist alone, along with the experimentally determined modulus of elasticity, can be used to predict the deflection of an isolated joist under a 1 kN point load. For Floor 1, this deflection is 8.2 mm at a span of 4.8 m. If full composite action of the joist and flooring is assumed, but with no interaction between joists, the deflection reduces to 4.2 mm. Notice that even this deflection is greater than that recorded for the floor. The difference is due to the transverse stiffness of the floor transferring load to the adjacent joists. The effectiveness of the transfer varies depending on the presence of solid blocking and a ceiling.

A elastic finite element model of Floor 1 was created using the finite element program, NISA (EMRC (1993)). In the model, the joists were modelled as three dimensional (3D) beam elements with actual material and stiffness properties. The particle board deck was modelled as a series of 3D general shell elements. General spring elements were used to model the nail connection between the deck and the joists. Similarly, the ceiling battens (3D beam elements) were connected to the joists with general spring elements to simulate the nailed connection. The ceiling lining was modelled as a series of 3D general shell elements fastened rigidly to the battens at the spring connections to the joists. Two rows of blocking were included, using 3D beam elements between the joists. A sketch of the general setup is shown in Figure 18.

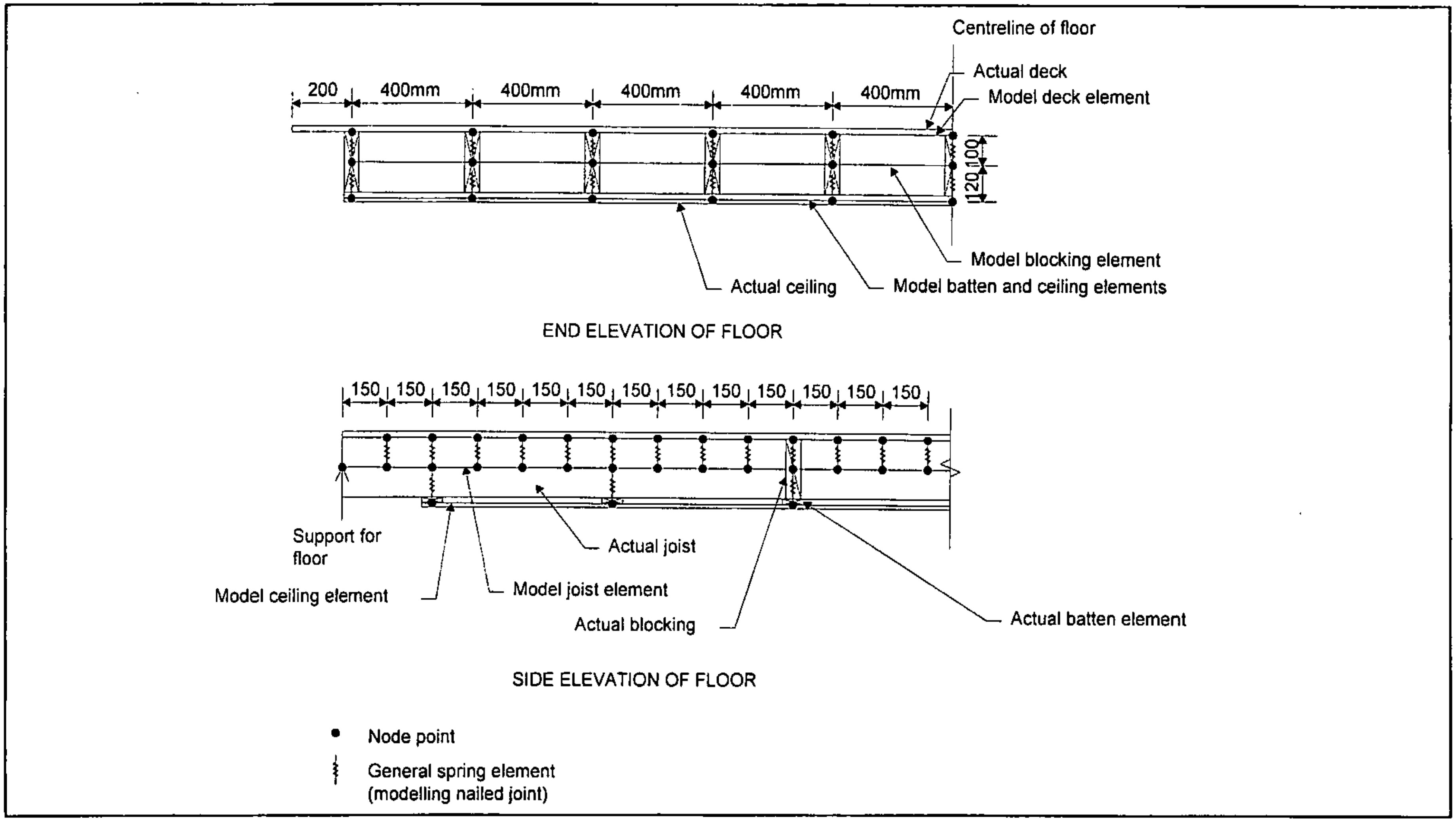

Figure 18: General setup of the NISA model

The model was built up progressively so that the output could be compared with the observed behaviour.

Initially, a 1 kN load was applied to the centre joist as a "stand alone" member. Measured stiffness properties were used for the model joist. The output deflection at the centre span of the joist, at 8.48 mm, matched very well the value of 8.2 mm, which was hand calculated using normal beam theory.

Next the floor deck was added to the model using thickness and stiffness properties from the manufacturer's literature. No test data was available to provide a shear stiffness for the nailed joint between the deck and the joists. Therefore, an estimated value of 10 kN/mm was used for the spring elements modelling the nails for displacements in the plane of the deck. A sensitivity analysis indicated that a ten times variation in this figure caused little change in the model output. The model was found to overestimate the mid span deflection of the centre joist by a factor of 45% (2.9 mm versus 1.97 mm measured). The deflection of the joist 1.2m out from the centre matched reasonably well at approximately 0.1 mm. By increasing the joist modulus of elasticity in the model from the mean measured value of 9.7 GPa (see Table 1) to 12 GPa, the centre deflection from the model reduced to 2.46 mm. A comparison between the measured deflection profile and the model deflection profile for this case is presented in Figure 19. Unfortunately, there were a limited number of measured deflections for this case and so the comparison can only be made at three joists.

NZS 3603 section 3.2.7 (SNZ,1993) provides a method for distributing the effect of a concentrated load between joists, based on the stiffnesses of the joists and the decking. The method is more applicable to grid systems where the "crossing" members are individual timber members, rather than sheet decking. Nevertheless, by applying the method to Floor 1, the prediction of the centre joist deflection, under the 1 kN point load, is 2.9 mm. This figure is the same as the computer model output using the measured modulus of elasticity for the joist, indicating that the codified procedure is reasonably accurate.

The ceiling battens and ceiling were added to the model next. The mid span deflection of 1.91 mm was almost double the measured mid span deflection recorded in the experimental work. However, in the experimental work, there were always two rows of blocking present when the ceiling was in place, to provide the shear transfer between the deck and the ceiling, so this comparison was of little relevance.

Blocking was added to the model and the ceiling battens were disconnected from the joists. A reasonable match was achieved between the model and the experimentally obtained deflection distribution (see Figure 19). Ideally, the connection between the blocking and the joists should have been modelled to represent the end nailing present in the experimental specimen but a 3D beam element rigidly connected to the joists was used for simplicity.

Finally, the ceiling battens were reconnected to the joists. The resulting deflection distribution confirmed the importance of the blocking working in combination with the deck and ceiling to provide a transversely stiff floor. While the mid span deflection of the centre joist matched the experimental value very well (0.95 mm compared to a measured value of 0.97 mm) the computer model generated greater deflections for the outer joists (Figure 19). Artificial adjustment of the blocking stiffness failed to improve the deflection distribution match with the experimental specimen.

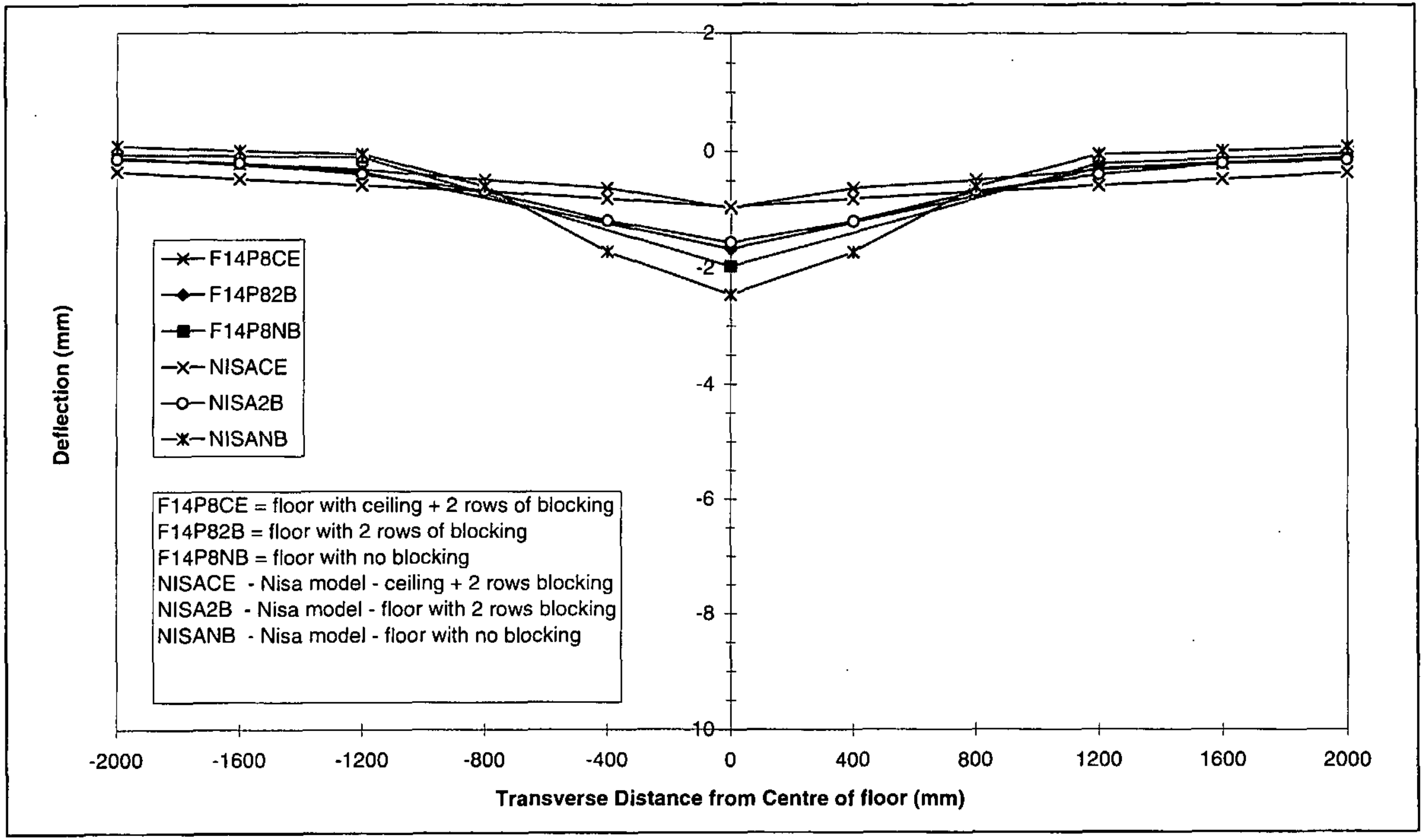

Figure 19: Comparison between measured static deflections and NISA model output deflections

4.3 Dynamic Behaviour

The dynamic behaviour of the three floors is presented in Tables 2 to 5, along with the test summary, for convenience. It was generally possible to identify the modal frequencies from the FFT plots without difficulty. An example FFT plot is presented in Figure 20. The symmetric nature of the test setups meant that the responses from the two accelerometers positioned 1200 mm away from the centre of the floor were similar. These accelerometers also tended to follow the behaviour of the centre accelerometer. On occasions they produced frequency peaks which didn't correspond to the output from the centre accelerometer. It is postulated that these peaks were due to transversely occurring frequency oscillations, where the centre accelerometer was not affected, because it was positioned on a node point. There were insufficient accelerometers to be able to identify mode shapes.

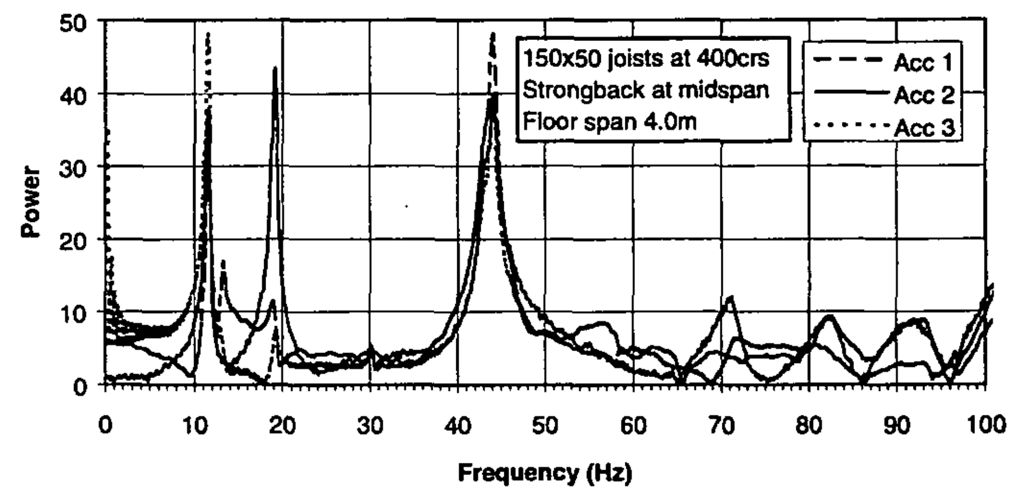

Figure 20: Results of FFT Analysis on Floor 3 Run 2 Accelerations

The following general observations applied to all floors:

- Reducing the span had the effect of increasing the first mode natural frequency, especially when the overhanging ends of the floor were propped.
- The addition of blocking increased the first mode natural frequency - two rows of blocking did not change the first mode natural frequency from the one row of blocking case although higher modes were more significantly affected.
- Propping the outermost joists to simulate four sided support significantly stiffened the floors and increased the frequency responses as a consequence.

- The addition of ceiling battens and ceiling lining caused little change to the first mode natural frequency because the additional stiffness was offset by the extra mass.
- Higher frequency modes were influenced by the addition of the ceiling.
- Damping ratios for the bare floors tended to be about 2%.
- The addition of one person mildly increased the damping.
- The addition of four people significantly increased the damping.

With respect to Floor 2 only:

- Gluing the flooring to the joists did little to change the natural frequencies of the floor.
- The addition of carpet and underlay did little to alter the natural frequencies and damping of the floor.
- The addition of inanimate mass caused a reduction in the first mode natural frequency but did nothing to alter the damping.
- Excitation of the cantilever section of floor produced a first mode natural frequency at the centre of the simply supported span that was approximately 4 Hz less than the same span with no cantilever, due to the dynamic oscillation of the cantilever section.

With respect to Floor 3 only:

- The addition of a strongback made little difference to the natural frequencies or damping.

4.4 Theoretical Prediction of Dynamic Behaviour

The prediction of the dynamic behaviour of the floors was undertaken using the spreadsheet formulated by King (1997) based on Ohlsson's theory (1988). Inputs to the spreadsheet include:

Joist properties

- material
- depth
- width
- span
- spacing
- modulus of elasticity
- density

Deck properties

- material
- thickness
- width

- density
- modulus of elasticity
- effectiveness of connection to joists

Transverse blocking properties

- material
- depth
- width
- density
- modulus of elasticity
- effectiveness

Ceiling battens

- material
- depth
- width
- density
- modulus of elasticity
- spacing

Ceiling lining

- material
- thickness
- density
- modulus of elasticity
- percentage continuity to joists

Ohlsson (1988) suggests that for normal residential occupancies the damping be set at 1% in the analysis.

From the above input data, the spreadsheet:

- calculates the self weight of the floor
- calculates sectional properties along the joist
- undertakes a static serviceability check under the self weight and applied live loads
- calculates the stiffness ratio between the along joist and the orthogonal directions
- calculates the first mode natural frequency, number of modes less than 40 Hz (N_{40}), and maximum unit impulse velocity of the floor; and
- grades the performance as good, doubtful or clearly unacceptable.

The process was somewhat iterative in that the effectiveness of the decking, blocking and ceiling is not definitely known. However, sensitivity analyses showed that:

- a 0% to 100% variation in deck continuity significantly affects the natural frequency but the N_{40} value change is very small.
- a 0% to 100% variation in the blocking effectiveness does not affect the first mode natural frequency but changes the N_{40} value. The N_{40} change is significant between 0% and 60% blocking effectiveness.
- a 0% to 100% variation in the ceiling continuity affects the natural frequency but has only a minor effect on the N_{40} value.

The spreadsheet model assumes that there is no end fixity provided for the floor. The side edges are assumed to be supported.

For each of the configurations for the floor specimens that were investigated in the laboratory, a model was generated using the spreadsheet. Actual data was able to be included for the physical and material properties but estimates of continuities and effectiveness had to be made. Adjustments were made to these to match the first mode natural frequency and the N_{40} value obtained from the FFT analysis of the experimental results.

4.5 Comparison of Theoretical and Experimental Dynamic Behaviour

In all of the comparisons made in this section, the damping was assumed to be 1%, in line with Ohlsson's (1988) recommendation.

4.5.1 Floor 1

A summary of the theoretical behaviour predictions is presented in Table 8.

For all spans of Floor 1, to obtain a match between the theoretical and the experimental first mode frequency and the number of modes less than 40, (N_{40}), a value of 55% was consistently required for the deck continuity, regardless of the presence of blocking or ceiling lining. To match the two parameters when blocking was added, the blocking effectiveness was required to be 40% with a single row and 50% with two rows. With the addition of the ceiling lining, the effectiveness of the ceiling was required to be 50% to make the parameters match. Interestingly, the blocking effectiveness was required to increase to 70% when the ceiling was included. This is likely to be caused by the composite action of the deck, the blocking and the ceiling. In the unblocked case, it wasn't possible to obtain a match of the N_{40} value because it is only influenced by the blocking effectiveness and there was no blocking present.

With the above effectiveness percentages incorporated, King's (1997) spreadsheet indicated that the unblocked floor would have a "doubtful" performance at 4.8m and 4.2m spans. At 3.6m, the performance was considered to be "good". At all three spans it was not possible to match the N_{40} value, as it is only influenced in a minor way by the deck continuity.

When one row of blocking was added, the performance at all three spans was upgraded to "good". With two rows of blocking and a ceiling, the performance was also classified as "good".

There appear to be anomalies in the application of Ohlsson's theory. In the case of no blocking, King's spreadsheet suggests that doubtful performance would be encountered when the floor span reached 3.75m, which seems reasonable, bearing in mind that the maximum span for nominal 200 x 50 joists at 400 centres in NZS 3604 (1990) is 3.8m. However, as soon as a single row of blocking is added, the spreadsheet indicates that all spans up to 6m are good. Greater spans would also be acceptable but for the mode frequency dropping below 8 Hz, making the application of the theory inappropriate. Similarly, with 2 rows of blocking and a ceiling, the spans at which the frequency drops below 8 Hz are respectively 5.9m and 5.7m. The apparent decrease in "acceptable" span as the transverse stiffening increases is anomalous and suggests that Ohlsson's theory is flawed.

Table 8: King's (1997) Spreadsheet Prediction of Performance for Floor 1

Span (m)	Blocking	Ceiling present?	Deck % continuity	Blocking % effective	Ceiling % effective	Freq. Match?	N_{40} match?	Spreadsheet classification
4.8	none	N	55	-	-	Y	N	Doubtful
4.2	none	N	55	-	-	Y	N	Doubtful
3.6	none	N	55	-	-	Y	N	Good
4.8	1 row	N	55	50	-	Y	Y	Good
4.2	1 row	N	55	40	-	Y	Y	Good
3.6	1 row	N	55	40	-	Y	Y	Good
4.8	2 rows	N	55	50	-	Y	Y	Good
4.2	2 rows	N	55	50	-	Y	Y	Good
3.6	2 rows	N	55	50	-	Y	Y	Good
4.8	2 rows	Y	55	70	50	Y	Y	Good
4.2	2 rows	Y	55	70	50	Y	Y	Good
3.6	2 rows	Y	55	70	50	Y	Y	Good

N = No Y = Yes

4.5.2 Floor 2

A summary of the theoretical behaviour predictions is presented Table 9.

Floor 2 comparisons were made for the cases of:

- nailed joints between the deck and the joists
- glued and nailed joints
- glued and nailed joints plus 0.15 kPa live load.

In the nailed case, as the span was reduced, it was necessary to reduce the deck continuity percentage, and to a lesser extent the blocking effectiveness, in King's (1997) spreadsheet in order to achieve a match between the first mode frequency and the N_{40} value. When the joints were glued, the deck continuity percentage had to be raised by approximately 20% to maintain the match. In all span cases on Floor 2 the spreadsheet indicated that the performance was "good". By artificially increasing the span in Floor 2, it was determined from the spreadsheet that the limiting criteria was the 8 Hz minimum first mode frequency and that a span of 5.7m would still provide "good" performance. This span is considerably greater than the maximum span of 3.25m allowed by NZS 3604 (1990).

With the addition of 0.15 kPa live load to the floor at 4.8m span King's (1997) spreadsheet rating was still "good". To obtain a match of parameters, the deck continuity was required to be set at 100% and the blocking effectiveness at 40%.

Table 9: King's (1997) Spreadsheet Prediction of Performance for Floor 2

Span (m)	Blocking	Glued deck joint ?	Deck % continuity	Blocking % effective	Freq. match?	N_{40} match ?	Live load (kPa)	Spreadsheet classification
4.8	1 row	N	60	40	Y	Y	-	Good
4.0	1 row	N	40	30	Y	Y	-	Good
3.2	1 row	N	20	30	Y	Y	-	Good
4.8	1 row	Y	55	50	Y	Y	-	Good
4.0	1 row	Y	55	40	Y	Y	-	Good
4.8	1 row	Y	100	40	Y	Y	0.15	Good

N = No Y = Yes

4.5.3 Floor 3

A summary of the theoretical behaviour predictions is presented in Table 10.

Comparisons between theoretical and experimental behaviour were made for Floor 3 for the cases of no blocking, one row of blocking and one row of blocking plus ceiling. In the case of no blocking, as the span reduced it was necessary to reduce the deck continuity percentage in order to maintain the match between predicted first mode frequency. Note that for Floor 1, where the joist spacing was 400 mm, the deck continuity percentage remained constant. It was not possible to match the N_{40} value for the same reason as outlined for Floor 1. King's (1997) spreadsheet indicated a "doubtful" performance for all spans without blocking. The addition of one row of blocking, at 70% effectiveness, shifted the rating for the 4m span to "good". The 3.4m and 2.8m spans were not investigated. Further, addition of a ceiling resulted in a "good" performance rating from the spreadsheet at all three spans. To maintain the parameter match between theory and experiment, it was necessary to reduce the deck continuity percentage as the span reduced, which wasn't consistent with the constant value requirement with Floor 1.

Table 10: King's (1997) Spreadsheet Prediction of Performance for Floor 3

Span (m)	Blocking	Ceiling present ?	Deck % continuity	Blocking % effective	Ceiling % effective	Freq. match?	N_{40} match?	Spreadsheet classification
4.0	none	N	55	-	-	Y	N	Doubtful
3.4	none	N	40	-	-	Y	N	Doubtful
2.8	none	N	30	-	-	Y	Y	Doubtful
4.0	1 row	N	55	70	-	Y	Y	Good
4.0	1 row	Y	80	100	75	Y	Y	Good
3.4	1 row	Y	45	100	45	Y	Y	Good
2.8	1 row	Y	20	75	25	Y	Y	Good

N = No Y = Yes

4.6 Influence of Damping in the Theoretical Prediction

Ohlsson (1990) suggests the use of 1% as the damping value for domestic floors. In the course of the present experimental work, analysis of FFT records indicated that a figure of 2% was more applicable for bare floors. A brief sensitivity analysis showed that the vibration acceptability assessment was very heavily influenced by the damping value used. Substitution of 2% into King's (1997) spreadsheet would convert all of the "doubtful" performances to "good", which appears to make the accuracy of the prediction worse. On the other hand, a reduction in the damping to 0.5% has a marked downward influence on the spreadsheet ratings. Clearly, the damping value that is used has a significant influence on the predicted behaviour.

5. DYNAMIC ASSESSMENT OF NEW FLOORS

5.1 Existing Ohlsson Assessment Procedure

The difficulty in using King's (1997) spreadsheet to predict the behaviour of floors before they are built is that there are not constant values for the effectiveness of the deck, blocking and ceiling that can be used. The present research has shown that as the span changes, so does the effectiveness of these items. Furthermore, there appears to be no constant relationship between the two which could be built into the spreadsheet.

Some conservative generalisations on the effectiveness of the various items can be made from the comparison between the experimental results and King's (1997) spreadsheet prediction. The following parameter values are suggested for use when the suitability of new floors is being assessed:

- When installed in conjunction with ceiling battens and plaster based ceiling linings, the effectiveness of one or two rows of blocking can be assumed to be at least 70%.
- The effectiveness of ceiling battens and plaster ceiling linings can be assumed to be approximately 45%, provided there is at least one row of blocking present.
- One row of blocking and no ceiling can be assumed to be approximately 40% effective.
- Two rows of blocking can be assumed to be at least 50% effective when there is no ceiling present.
- The deck continuity percentage appears to range from 20% at 3.2m span up to 60% at 4.8m span.
- The addition of adhesive between the deck and the joists does not make the deck any more effective than when there is no adhesive.

The cut-off criterion for a decision on whether a floor is "good" or "doubtful" using Ohlsson's method is given by the equation:

$$V_{max} = 10.100^{\sigma_0}$$

where

V_{max} = maximum unit impulse velocity (mm/s/Ns)

σ_0 = damping coefficient (s^{-1})

= $f_1.\xi$

where

f_1 = first mode natural frequency (Hz)

ξ = damping ratio

If V_{max} is greater than the right hand side of the equation, then the floor performance is uncertain. When the constant factor, 10, is replaced with 20 and the right hand side of the equation is still smaller than the left, then the performance is "unacceptable". The unconservative results of this study suggest that the constant factor, 10, should be replaced with a lesser value to provide a more realistic representation of the in-service conditions encountered in New Zealand. Furthermore, the damping should be increased to 2% to more accurately represent the observed behaviour of the tested floors. The relationship between impulse velocity and damping coefficient proposed by Ohlsson is reproduced in Figure 21.

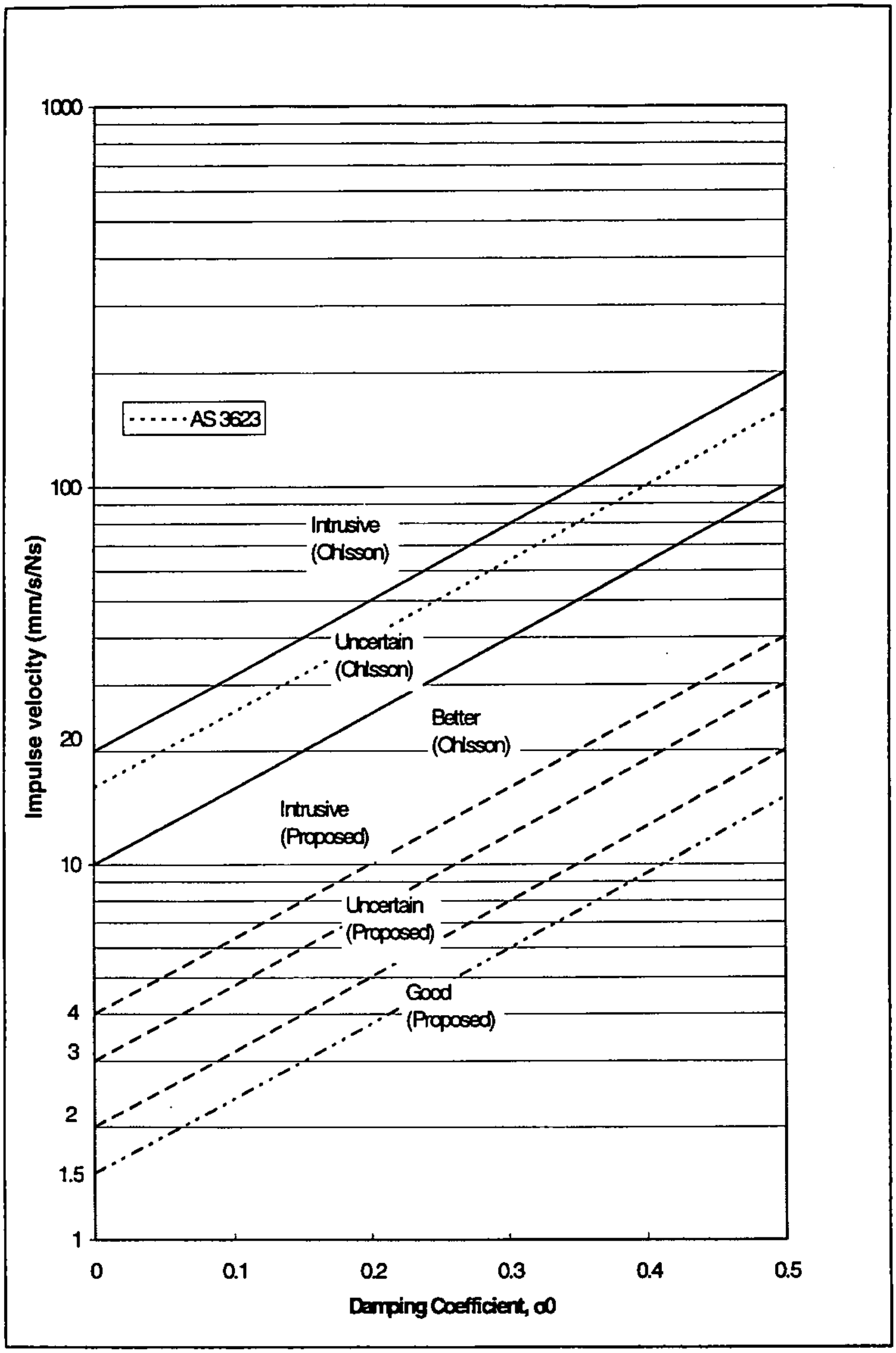

Figure 21: Proposed floor classification graph

5.2 Proposed Revision to the Ohlsson Assessment Procedure

A comparison was made between the existing NZS 3604 (1990) maximum spans, the maximum spans predicted by Chui and Smith (1990) and predicted using a modified Ohlsson equation, for the three joist configurations tested.

These are presented in Table 11. In calculating the maximum span using the Ohlsson procedure, the constant term has been reduced from that recommended by Ohlsson. Column 5 of Table 11 gives the results for a constant of 1.5 for the transition between "good" and "uncertain" (the lowest line in Figure 21) and column 6 gives the results for a constant of 2.0 (the second lowest line Figure 21). The fourth line up from the bottom is a suggested transition from "intrusive" to "uncertain" to be used in conjunction with the line second from the bottom (i.e. a constant value of 4.0).

In the comparison, the 8 GPa characteristic modulus of elasticity for No 1 framing in NZS 3603 was used. This may be greater than will be expected from second generation pine in the future. A reduction in the modulus of elasticity will lead to a reduction in joist span.

Table 11: Comparison of Maximum Joist Spans Using Various Procedures

Joist size and spacing	NZS 3604 max. span (m)	Chui & Smith max. span (m) (no ceiling)	Modified Ohlsson max. span (m) with blocking ($\xi = 1\%$) Constant =2.0	Chui & Smith max. span (m) (ceiling included)	Modified Ohlsson max. span (m) with blocking and ceiling ($\xi = 2\%$) Constant = 1.5	Modified Ohlsson max. span (m) with blocking and ceiling ($\xi = 2\%$) Constant = 2.0
200 x 50 @ 400 centres	3.8	3.55	3.65	3.6	3.4	3.7
200 x 50 @ 600 centres	3.25	3.0	3.25	2.9	3.0	3.25
140 x 45 @ 400 centres	2.8	2.5	2.4 (no blocking)	2.5	2.45	2.6

It can be seen from Table 11 that there is not a large difference between the Modified Ohlsson prediction and Chui and Smith when a constant of 1.5 is used. The difficulty with validation of any of these predictions is that a subjective judgement is required by people using the floor. From the limited experimental work undertaken in this study, it is proposed that the spans predicted using a constant of 2.0 are acceptable.

Further work is required to obtain unbiased subjective assessments of the performance of a range of New Zealand floor spans so that the modified Ohlsson prediction can be validated.

For comparison, joist spans predicted by the modified Ohlsson procedure (damping of 2% and constant term of 2.0), using the appropriate parameter settings from Section 5 and joist modulus of elasticity of 8 GPa, are presented in Table 12.

Table 12: Predicted Maximum Joist Spans Using the Modified Ohlsson Procedure

Nominal Joist Size	Joist spacing 400 mm			Joist spacing 450 mm			Joist spacing 600 mm		
	3604*	Ohlsson (1)	Ohlsson (2)	3604*	Ohlsson (1)	Ohlsson (2)	3604*	Ohlsson (1)	Ohlsson (2)
100 x 50	1.80	1.85	1.95	1.75	1.80	1.90	1.25	1.70	1.80
125 x 50	2.30	2.15	2.30	2.20	2.10	2.25	1.60	2.00	2.10
150 x 40	2.60	2.35	2.60	2.50	2.30	2.60	1.80	2.20	2.35
150 x 50	2.80	2.40	2.65	2.70	2.35	2.70	2.00	2.25	2.45
200 x 50	3.80	3.65	3.70	3.60	3.50	3.55	3.25	3.25	3.25
225 x 50	4.30	4.30	4.25	4.10	4.05	4.15	3.75	3.65	3.70
250 x 50	4.80	4.80	4.85	4.60	4.75	4.70	4.15	4.20	4.20
300 x 50	5.75	5.95	6.10	5.50	5.90	5.80	5.00	5.10	5.25

* NZS 3604:1990
(1) no ceiling present and blocking to satisfy NZS 3604
(2) plasterboard ceiling on battens present and blocking to satisfy NZS 3604

It should be noted that the spans predicted in Table 12 take no account of imposed live load. Designers would still need to check live load deflections and strength for live loads greater than 1.5 kPa as they may govern the maximum allowable span.

6. CONCLUSIONS AND RECOMMENDATIONS

This work has shown that the natural frequency modes of timber floors with joists can be identified by exciting the floor using a loose bag containing approximately 4 kg of lead shot dropped from 500 mm, and recording the acceleration response of the floor. A Fast Fourier Transform (FFT) of the recorded signal yields the values of the frequency modes and also the number of modes less than 40 Hz.

It has also been shown that reasonable predictions of the first mode natural frequency and the number of frequencies less than 40 Hz can be made using King's (1997) spreadsheet based on Ohlsson's (1988) theory, provided the correct effectiveness percentages are included for the decking, the presence of blocking, and the presence of ceilings. Difficulty arises in predicting whether or not the floor will be dynamically suitable.

The dynamic suitability of timber floors with joists has been previously noted in this report as being largely subjective. In the limited scope of the study, the performance of the larger span floors was subjectively judged to be unsatisfactory while the application of Ohlsson's theory indicated that the performance was acceptable. It has hence been concluded that the use of the Ohlsson theory in its present form, for prediction of behaviour, is ineffective. A modification to the constant term from 10 to 2, and the use of a more realistic damping of 2% in Ohlsson's equation for the relationship between the maximum unit impulse velocity, the first mode frequency and the damping, was shown to greatly improve the accuracy of Ohlsson's prediction of behaviour for the case of New Zealand floors.

Further research is required to calibrate qualitative assessments of the suitability of timber floors against the quantitative predictions of the modified Ohlsson model derived in this investigation.

A modified set of joist span tables which could be used in NZS 3604 and which take account of the serviceability effects of vibration has been produced, based on the modified Ohlsson procedure.

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