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DYNAMIC SERVICEABILITY DESIGN OF ATTIC ROOM FLOORS IN MODERN TIMBER FRAME HOUSES

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Abstract: In this paper, the vibrational performance of roof trusses for constructing the attic room floors with various geometric configurations was investigated using commercial finite element software – SAP2000. Vibrational parameters included the mid-span deflections of the bottom chord under dead loads and unit point load, and modal frequencies up to 40 Hz and modal shapes. This study confirmed that increasing the bottom chord size and including composite bottom chord and fully composite roof truss members could largely enhance the dynamic serviceability performance of the attic room floors in timber frame houses.

1 INTRODUCTION

Timber frame houses have become common construction worldwide. It is estimated that across the developed countries, timber frame accounts for around 70% of all housing stock, representing some 150 million homes. Roof trusses in timber frame houses are normally constructed from solid timber sections connected by traditional carpentry joints or punched metal plates. In timber frame houses, spacious attic rooms can be created for residence. The design of roof trusses is fairly complex, with the ultimate limit state criteria for checks against bending, shear, axial loading, bearing and lateral stability under various design loads and the serviceability limit state criteria for checks against deflection and vibration. Eurocode 5 Part 1-1 [1,2] together with National Annex [3] provides useful methods for designing these components. As for vibrational serviceability design, there are no ready formulae except a proposed lower limit of 8 Hz for the fundamental frequency. Vibrational performance of attic room floors is a serviceability issue, but not much has been done on this type of structures yet.

Previous research work was conducted to systematically identify the effects of different geometric parameters on the dynamic performance of the flooring system in the attic room of timber framed buildings [4]. The serviceability parameters for assessing the dynamic performance of the roof structure included the mid-span deflection under dead loads, the relative mid-span deflection under 1 kN point load and the fundamental frequency. The influencing parameters included bracing configuration, floor span of the attic room, roof pitch angle and construction process. The dynamic performance for both single trusses and a complete assembly of roof trusses for an attic room was analysed. The results show that properly arranged bracings, decreased floor span and increased roof pitch angle could all enhance the dynamic performance of attic room floors. The roof truss assembly could also effectively enhance the dynamic performance of attic rooms by largely decreasing the unit point load deflection due to the redistribution of the applied load to the neighbouring trusses.

However, the design case in the previous study, claimed as a satisfactory design case, was confirmed to fail to satisfy the requirements for the unit point load defection and fundamental frequency to Eurocode 5. For example, the final mid-span deflection relative to the walls of the attic room under 1 kN point load at the mid-span of the floor for the assembly was 1.97 mm, which was largely higher than the limit of 1.37 mm for the attic room floor span of 5.0 m according to the UK National Annex to EN 1995-1-1 [3]. The first in-plane vibration frequency f_1, corresponding to an asymmetric vibration mode with the inflection point located at the centre of the single truss or the attic room floor, was only 2.47 Hz for the single truss and 2.73 Hz for the roof truss assembly, respectively. Even the second in-plane vibration frequency f_2, which was corresponding to a symmetric vibration mode and could be used for the control of floor design, was still only 4.36 Hz for the single roof truss and 4.39 Hz for the roof truss assembly. All these values were well below the minimum requirement of 8 Hz proposed for residential buildings in EN 1995-1-1. Therefore, further research is still needed to systematically assess the effects of geometric dimensions and configurations on the dynamic performance of the attic room floor, to propose the realistic design equations for calculating the mid-span deflections and fundamental frequency, and eventually to ensure the whole design of the attic room floor satisfy all the requirements set by the design codes.

In this paper, attention was paid to the assessment of the vibrational performance of roof trusses for constructing the attic room floors with various geometric configurations using the commercial finite element software – SAP2000 [5]. Vibrational parameters included mid-span deflections of the bottom chord under dead loads and unit point load, and modal frequencies up to 40 Hz and modal shapes. The parameters to be studied included bottom chord size, composite bottom chord and fully composite roof truss members.

2 CRITERIA FOR TIMBER FLOOR VIBRATIONAL SERVICEABILITY

In Eurocode 5 Part 1-1, there are three criteria for assessing the vibrational serviceability for design of timber flooring systems, including the floors for attic rooms.

2.1 Fundamental frequency

EN 1995-1-1 requires that the fundamental frequency of residential floors or the first modal frequency, f_1, should satisfy the following equation

$$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_{\mathrm{L}}}{m}} > 8\ \mathrm{Hz} \tag{1}$$

where m is the mass per unit floor area in kg/m^2, L is the floor span in m, and $(EI)_{\mathrm{L}}$ is the equivalent plate bending stiffness of the floor about an axis perpendicular to the beam direction in Nm^2/m.

2.2 Unit point load deflection

For residential floors with f_1 > 8 Hz, the maximum instantaneous vertical deflection caused by a unit point load, w, should satisfy the following equation

$$w \leq a \text{ (mm/kN)} \tag{2}$$

where a is the design limit for the deflection of the timber floor under unit point load in mm/kN. In the UK, a is proposed as follows [3]:

$$a = \begin{cases} 1.80 & \text{mm/kN} \quad \text{for } L \leq 4000 \text{ mm} \\ 16500/L^{1.1} & \text{mm/kN} \quad \text{for } L > 4000 \text{ mm} \end{cases} \tag{3}$$

2.3 Unit impulse velocity response

For residential floors with f_1 > 8 Hz, the unit impulse velocity response or the maximum velocity caused by a unit impulse, v, should satisfy the following equation

$$v \leq b^{(f_1 \zeta - 1)} \text{ (m/(Ns}^2\text{))} \tag{4}$$

where b is a parameter depending on a, and ζ is modal damping ratio, given as $\zeta = 0.01$ in EN 1995-1-1 but revised as 0.02 in the UK. For a rectangular floor with overall dimensions $B \times L$, simply supported along all four edges, the value v may be taken as

$$v = \frac{4(0.4 + 0.6 n_{40})}{m B L + 200} \text{ (m/(Ns}^2\text{))} \tag{5}$$

where B is the floor width in m, n_{40} is the number of first-order modes with frequencies up to 40 Hz, given as follows

$$n_{40} = \frac{B}{L}\left\{\left(\left(\frac{40}{f_1}\right)^2 - 1\right)\frac{(EI)_L}{(EI)_B}\right\}^{1/4} \tag{6}$$

and $(EI)_B$ is the equivalent plate bending stiffness of the floor about an axis parallel to the beam direction in Nm^2/m.

3 MODELLING OF ROOF TRUSS FOR ATTIC ROOM FLOORS

Similar to the previous study by the authors [4], the same overall geometric dimensions for roof trusses were maintained. Figure 1 shows the duo-pitch roof truss with a span of 8.5 m and the pitch angle $\alpha = 45°$, forming an attic room space of span × height = 5.0 m × 2.34 m. TR26 solid timber [6] was assumed for constructing the roof truss, with a mean Young's modulus $E = 11000$ N/mm^2 and a mean density $\rho = 450$ kg/m^3. Top chord had a dimension of 47 mm × 197 mm, bottom chord had a dimension of 47 mm × 222 mm which was revised from the original dimension of 47 mm × 197 mm, vertical bracings had a dimension of 47 mm × 122 mm, and the tie had a dimension of 47 mm × 97 mm. The roof truss was assumed to be simply supported at the ends of the bottom chord with the horizontal projection of 450 mm for the overhang at each side.

To assess the effect of the variations of bracing members on the serviceability performance of the truss structure, ten geometric configurations of bracings were created where Model 1.1

was used as the bench mark, as shown in Figure 2. Extra single or multi bracing members of 47 mm × 72 mm were added either only in the triangular regions next to the supports (Models 1.2 to 1.5 and 1.8), or in the same triangular regions together with the region between the ridge point and tie members. For Model 1.4, two extra skew bracing members were added into the basic Model 1.1 within the bottom corner triangular regions, see the thick grey lines in Figure 1. The top ends of these two skew bracing members were connected to the joints between the top chords and vertical bracing members, while the bottom ends of the skew members were connected to the bottom chord but at 1/3 the horizontal distance of the triangular region to the joints between the bottom chord and vertical bracing members.

SAP2000 was used for both static and dynamic analyses. The tie and vertical bracings were assumed to be pinned at both ends. The two top chords were assumed to be pinned at the ridge, and the bottom chord pinned at both ends. All the chords were assumed to be continuous over the whole length.

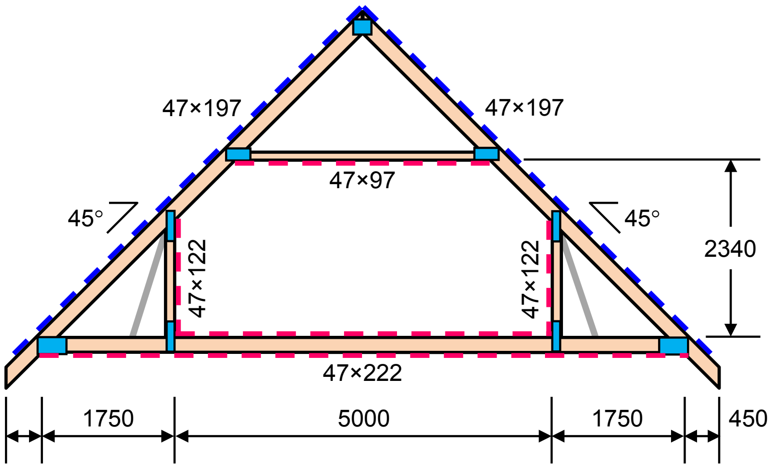


Figure 1: Due-pitch roof truss structure

4 DEFLECTIONS DUE TO DEAD LOADS

Table 1 lists the static deflections of the bottom chord at mid-span, w, under dead loads for all ten models. For comparison, the mid-span static deflections of the roof truss with the bottom chord of 47 mm × 197 mm are also included in the table. The limit for the static mid-span deflection of the bottom chord under combined dead load and part of imposed load is $L/250 = 8500/250 = 34.0$ mm in the UK. The deductions in the static mid-span deflection in percentage compared with those for Model 1-1 are included in Table 1 as well.

Table 1: Static defletions at mid-span under dead loads for various models

Model	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10
w^a (mm)	13.01	12.52	12.47	12.46	11.51	11.49	11.49	11.49	12.41	12.44
Deduction (%)	/	3.77	4.15	4.23	11.53	11.68	11.68	11.68	4.61	4.38
w^b (mm)	5.25	5.13	5.12	5.13	4.61	4.61	4.61	5.12	5.13	5.13
Deduction (%)	/	2.29	2.48	2.29	12.19	12.19	12.19	2.48	2.29	2.29

Note: ^{a} Bottom chord of 47 mm × 197 mm; ^{b} Bottom chord of 47 mm × 222 mm.

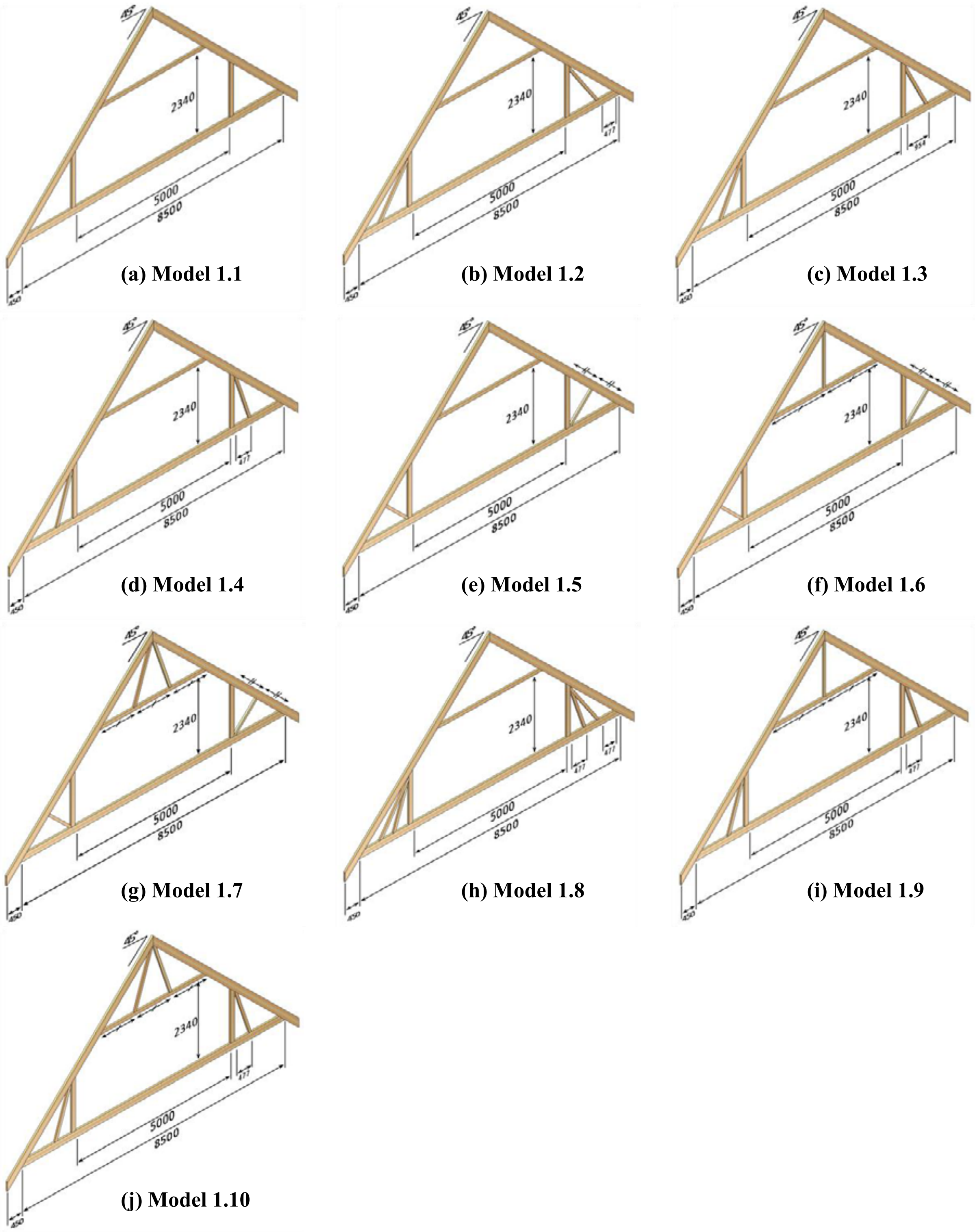


Figure 2: Due-pitch roof truss structure

For Model 1-1, comparing the static mid-span deflections for both bottom chord sizes indicates that the stiffness of the bottom chord increased by a factor of $(222/197)^3 = 1.431$ or up by 43.1% while the mid-span deflection decreased from 13.01 mm to 5.25 mm, down by 7.76 mm or 59.6%, which is larger than expected. This means that the increase in bottom chord size is a very effective way to reduce the mid-span deflection under dead loads.

Table 1 shows that for the roof trusses constructed with the bottom chord of 47 mm × 197 mm, Models 1.5 to 1.7 caused the biggest decrease of 12.2% in the deflection, representing a decrease of 0.64 mm if additional bracings were arranged in the way as shown in Figure 2. The addition of bracing members in the triangular regions or between the tie and roof ridge (Models 1.2 to 1.4 and 1.8 to 1.10) hardly influenced the deflection, with an increase of no more than 0.13 mm. All the calculated mid-span deflections were smaller than the design limit, but it should be mention that part of imposed load should be superimposed onto the dead loads.

5 DEFLECTIONS DUE TO UNIT POINT LOAD

Table 2 lists the relative deflections of the bottom chord between the mid-span and the attic wall positions, Δw, under a point load of 1.0 kN for all ten models. For comparison, the mid-span static deflections of the roof truss with the bottom chord of 47 mm × 197 mm at are also included in the table. The limit for the relative mid-span deflection of the bottom chord under 1 kN point load is $16500/L^{1.1} = 16500/5000^{1.1} = 1.41$ mm in the UK. The deductions in the static mid-span deflection in percentage compared with those for Model 1-1 are included in Table 2 as well.

Table 2: Static defletions at mid-span under unit point load for various models

Model	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10
Δw^a (mm)	3.97	3.72	3.64	3.60	3.89	3.89	3.89	3.57	3.60	3.60
Deduction (%)	/	6.30	8.31	9.32	2.02	2.02	2.02	10.08	9.32	9.32
Δw^b (mm)	2.96	2.83	2.78	2.77	2.89	2.88	2.88	2.75	2.76	2.76
Deduction (%)	/	4.39	6.08	6.42	2.36	2.70	2.70	7.09	6.76	6.76

Note: [a] Bottom chord of 47 mm × 197 mm; [b] Bottom chord of 47 mm × 222 mm.

For Model 1-1, comparing the static mid-span deflections for both bottom chord sizes indicates that the stiffness of the bottom chord increased by a factor of 1.431 or up by 43.1% and the mid-span deflection decreased from 3.97 mm to 2.96 mm, down by 1.01 or 25.4%, which is not as larger as that for the mid-span deflection under dead load. However, this still means that the increase in bottom chord size is a fairly effective way to reduce the mid-span deflection under unit point load.

Table 2 shows that for the roof trusses constructed with the bottom chord of 47 mm × 222 mm, Models 1.5 to 1.7 caused the biggest decrease of 12.2% in the deflection, representing a decrease of 0.64 mm if additional bracings were arranged in the way as shown in Figure 2. The addition of members in the triangular regions in the way as shown in Figure 2 and/or between the tie and roof ridge (Models 1.5 to 1.7) hardly influenced the deflection, with an increase of no more than 0.08 mm.

Obviously, the models with better performance under dead loads like Models 1.5 to 1.7 may not necessarily have good vibrational performance. There was only a decrease of up to 2.7% in Δw compared with other models. The addition of bracing members did not have to give better performance. The aim of this study is to reduce the flexibility or increase the stiffness of the floor of the attic room. Model 1.8 gave a slightly better result in Δw but was not very economical because two bracing members were added on each side. Models 1.9 and 1.10 used more bracing members between the ridge and tie but failed to give further enhancement. Hence, Model 1.4 would be the best option for considering the balance between the enhancement of dynamic performance and the cost.

6 MODAL FREQUENCIES AND SHAPES

The out-plane vibrations are assumed to be restrained by the components perpendicular to the roof truss plane, so only in-plane vibration modes are included. The modal frequencies up to 40 Hz and modal shapes are only considered because human beings are no longer sensitive to higher modes. Table 3 lists the first six in-plane modal frequencies for both models and Figure 3 shows the first six in-plane modes for Model 1.1 with the bottom chord of 47 mm × 222 mm. Table 4 lists the vibration frequencies of the first six modes for all ten models. For comparison, the first six in-plane modal frequencies for the roof truss with the bottom chord of 47 mm × 197 mm at mid-span are also included in the table.

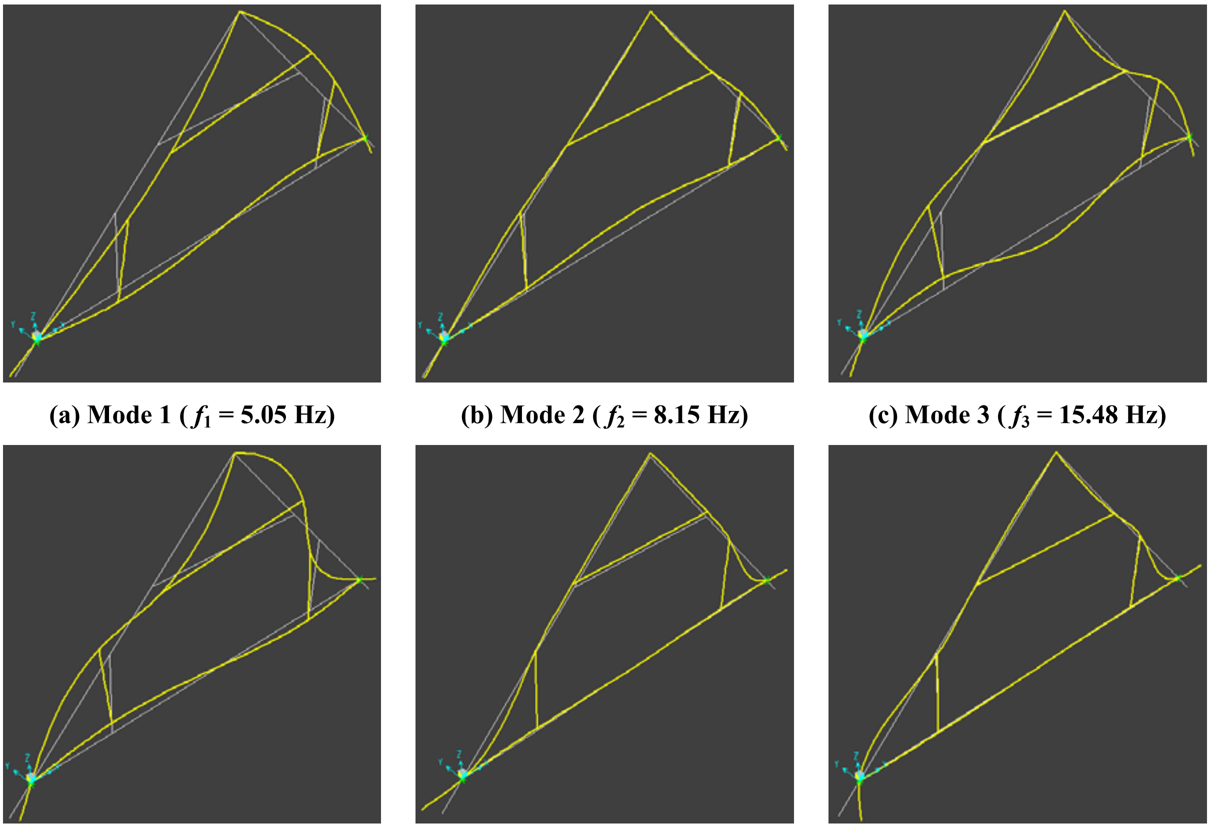
Table 3: Characteristics of first six in-plane frequencies

In-plane mode	1	2	3	4	5	6
Symmetry	Asymmetric	Symmetric	Symmetric	Asymmetric	Symmetric	Asymmetric
No of half sine waves	2	1	3	2	3	2

For Model 1-1, comparing the first two vibration frequencies for both bottom chord sizes indicates that with the increase in the stiffness of the bottom chord by a factor of 1.431 or up by 43.1%, the first frequency f_1 increased from 2.35 Hz to 5.05 Hz, up by 2.70 Hz or 114.9%, while the second frequency increased from 4.34 Hz to 8.21 Hz, up by 3.87 Hz or 89.2%. The increase only due to the change in the bottom chord size was about 100%, which is much larger than expected. Because Mode 1 had a second-order asymmetric vibration mode while Mode 2 had a first-order symmetric mode, it is reasonable to adopt the frequency for Mode 2, f_2, for design checks.

Table 4 indicates that for the roof trusses constructed with the bottom chord of 47 mm × 222 mm, the arrangements of the bracing members in Models 1.2 to 1.4 and 1.8 to 1.10 only slightly increased the fundamental frequency f_2 by up to 0.08 Hz or 1.0%. However the arrangements of the bracing members in Models 1.5 to 1.7 largely increased f_2 by 0.66 Hz or 8.1%. This means the latter arrangements were more effective for enhancing the fundamental frequency.

In practical design of timber flooring systems, the unit point load design criterion normally controls the overall design and is more difficult to be met than the criterion for the fundamental frequency. In this case, it can be seen that the most efficient roof truss in this series is Model 1.4 because it showed the largest improvement of the unit point load deflection compared to the rest. Hence, Model 1.4 was used as the bench mark truss, and the rest models would be disregarded even though the arrangements of the bracing members in Models 1.5 to 1.7 largely enhanced the fundamental frequency.



(a) Mode 1 (f_1 = 5.05 Hz) **(b) Mode 2 (f_2 = 8.15 Hz)** **(c) Mode 3 (f_3 = 15.48 Hz)**

(d) Mode 4 (f_4 = 16.40 Hz) **(e) Mode 5 (f_5 = 37.69 Hz)** **(f) Mode 6 (f_6 = 38.54 Hz)**

Figure 3: First six in-plane modes for Model 1.1

Table 4: First six in-plane modal frequencies for various models

Model	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10
f_1^a (Hz)	2.35	2.42	2.45	2.47	2.46	2.50	2.51	2.47	2.51	2.51
f_2^a (Hz)	4.29	4.34	4.35	4.36	4.56	4.56	4.56	4.36	4.36	4.36
f_3^a (Hz)	7.59	7.77	7.88	7.94	8.49	8.50	8.50	7.93	7.94	7.94
f_4^a (Hz)	8.67	8.68	8.70	8.71	9.94	10.05	10.05	8.69	8.82	8.83
f_5^a (Hz)	19.14	19.15	19.14	19.14	20.86	20.94	20.86	19.16	19.18	19.17
f_6^a (Hz)	19.58	19.58	19.59	19.59	22.34	22.33	22.34	19.59	19.59	19.59
Change in f_2^a (%)	/	1.17	1.40	1.63	6.29	6.29	6.29	1.63	1.63	1.63
f_1^b (Hz)	5.05	5.18	5.24	5.26	5.22	5.29	5.30	5.27	5.33	5.33
f_2^b (Hz)	8.15	8.21	8.23	8.22	8.81	8.81	8.81	8.22	8.22	8.22
f_3^b (Hz)	15.48	15.79	15.97	16.05	16.89	16.89	16.89	16.05	16.05	16.05
f_4^b (Hz)	16.40	16.42	16.45	16.46	18.60	18.76	18.77	16.42	16.62	16.63
f_5^b (Hz)	37.69	37.76	37.69	37.68	40.58	40.62	40.40	37.76	37.72	37.69
f_6^b (Hz)	38.54	38.54	38.54	38.54	43.98	43.98	43.98	38.54	38.54	38.54
Change in f_2^b (%)	/	0.74	0.98	0.86	8.10	8.10	8.10	0.86	0.86	0.86

Note: [a] Bottom chord of 47 mm × 197 mm; [b] Bottom chord of 47 mm × 222 mm.

7 EFFECT OF COMPOSITE BOTTOM CHORD ON STATIC AND DYNAMIC PERFORMANCE OF ROOF TRUSS

7.1 Modelling of composite bottom chord

In reality the attic room floor is composed of the bottom chord, the floor deck and the ceiling underneath the bottom chord. Here the floor was assumed to be constructed from 22 mm P5 chipboards as the floor deck with the Young modulus $E = 3$ kN/mm^2 and the 15 mm plasterboards as the ceiling with $E = 2$ kN/mm^2. First step was to create a composite I-beam in SAP 2000 and then replaced the bottom chord with this new beam, see Figure 4.

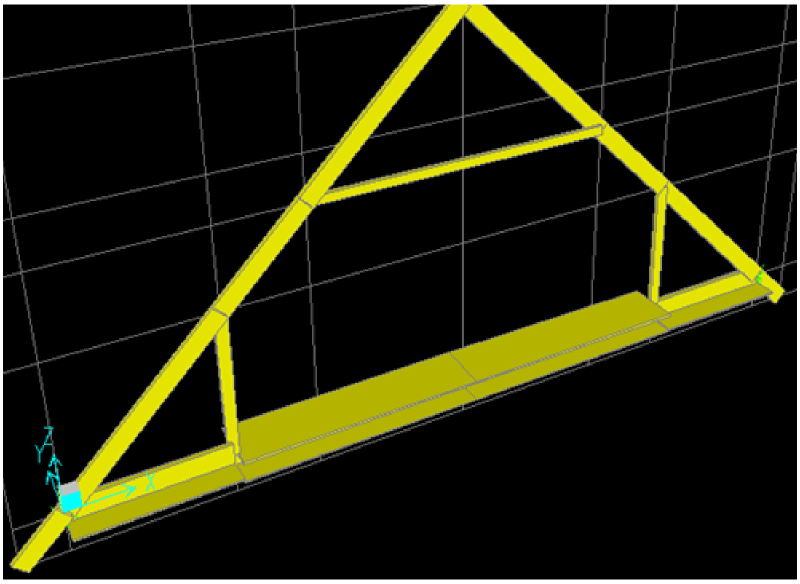


Figure 4: Composite I-beam element for the bottom chord in SAP2000

7.2 Modelling of composite roof truss members

The final modification is to assume all the truss members to be composite, see Figure 5. Both the wall and ceiling of the attic room were assumed to be decorated by the 15 mm plasterboards with $E = 2$ kN/mm^2. The roof was assumed to be 14 mm C16 solid timber with $E = 8000$ kN/mm^2 [7]

7.3 Static deflection due to dead loads

The calculated mid-span static deflections under dead loads for all ten models are listed in Table 5. For comparison, the corresponding results for the models without considering the composite effects. The mid-span static deflection for Model 1.1 with composite bottom chord decreased from 5.25 mm to 4.0 mm, down by 1.25 mm or 23.8%. Models 1.5 to 1.7 were more effective than other models for reducing the mid-span deflection under dead loads by 0.55 mm or 13.8%. The mid-span static deflection for Model 1.1 with full composite roof truss further decreased from 5.25 mm to 3.49 mm, down by 1.76 mm or 33.5%. Models 1.5 to 1.7 were still more effective than other models for further reducing the mid-span deflection under dead loads by 0.54 mm or 15.5%.

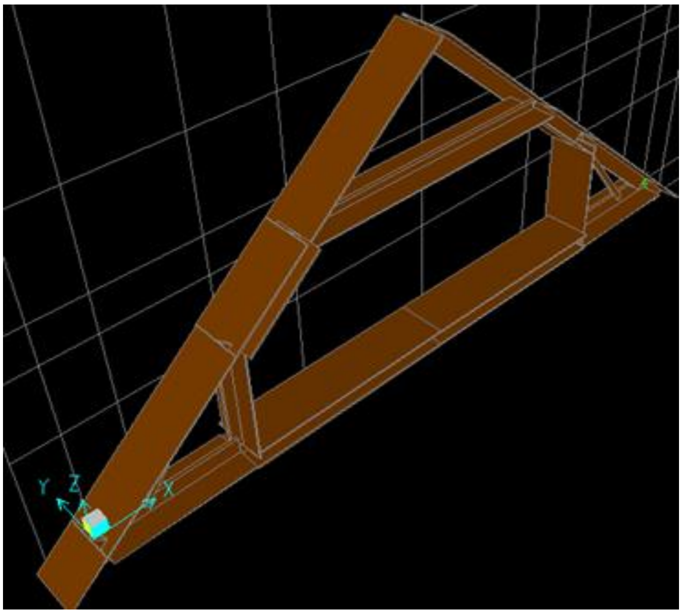


Figure 5: Composite elements for the duo-pitch roof truss in SAP2000

Table 5: Static defletions at mid-span due to dead loads for various models

Model	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10
w^a (mm)	13.01	12.52	12.47	12.46	11.51	11.49	11.49	11.49	12.41	12.44
w^b (mm)	5.25	5.13	5.12	5.13	4.61	4.61	4.61	5.12	5.13	5.13
w^c (mm)	4.00	3.96	3.97	3.99	3.45	3.44	3.44	3.99	3.99	3.99
Deduction in w^c (%)	/	1.00	0.75	0.25	13.75	14.00	14.00	0.25	0.25	0.25
w^d (mm)	3.49	3.45	3.45	3.47	2.96	2.95	2.95	3.46	3.46	3.46
Deduction in w^d (%)	/	1.15	1.15	0.57	15.19	15.47	15.47	0.86	0.86	0.86

Note: [a] Bottom chord of 47 mm × 197 mm; [b] Bottom chord of 47 mm × 222 mm;
[c] Bottom chord of 47 mm × 222 mm with composite effect; [d] All truss members composite.

7.4 Static deflection due to unit point load

The calculated mid-span deflections under unit point load for all ten models are listed in Table 6. For comparison, the corresponding results for the models without considering the composite effects are included in the table. The mid-span static deflection under unit point load for Model 1.1 with composite bottom chord decreased from 2.96 mm to 1.76 mm, down by 1.20 mm or 40.5%. Models 1.2 to 1.4 and 1.8 to 1.10 were more effective than other models for reducing the mid-span deflection by up to 0.10 mm or 5.7%. The mid-span static deflection under unit point load for Model 1.1 with full composite roof truss further decreased from 2.96 mm to 1.74 mm, down by 1.22 mm or 41.2%. Models 1.2 to 1.4 and 1.8 to 1.10 were still more effective than other models for further reducing the mid-span deflection by 0.10 mm or 5.7%.

Comparing the variation trends for the mid-span static deflections under dead loads and unit point load indicates that the mid-span deflection under dead loads could be largely enhanced by considering both the bottom chord and rest roof truss members to be composite while the mid-span deflection under unit point load could only be largely enhanced by adopting composite bottom chord and further compositing the rest members did not show large improvement.

Table 6: Static defletions at mid-span due to unit point load for various models

Model	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10
Δw^a (mm)	3.97	3.72	3.64	3.60	3.89	3.89	3.89	3.57	3.60	3.60
Δw^b (mm)	2.96	2.83	2.78	2.77	2.89	2.88	2.88	2.75	2.76	2.76
Δw^c (mm)	1.76	1.70	1.69	1.67	1.70	1.70	1.70	1.66	1.68	1.68
Deduction in Δw^c (%)	/	3.41	3.98	5.11	3.41	3.41	3.41	5.68	4.55	4.55
Δw^d (mm)	1.74	1.67	1.66	1.65	1.68	1.68	1.68	1.64	1.65	1.66
Deduction in Δw^d (%)	/	4.02	4.60	5.17	3.45	3.45	3.45	5.75	5.17	4.06

Note: [a] Bottom chord of 47 mm × 197 mm; [b] Bottom chord of 47 mm × 222 mm;
[c] Bottom chord of 47 mm × 222 mm with composite effect; [d] All truss members composite.

7.5 Modal frequencies

The calculated first six vibration frequencies for all ten models are listed in Table 7. For comparison, the corresponding results for the models without considering the composite effects. The second frequency for Model 1.1 with composite bottom chord increased from 8.15 Hz to 9.06 Hz, up by 0.91 Hz or 11.2%. Models 1.5 to 1.7 were more effective than other models for enhancing the second vibration frequency by 0.99 Hz or 10.9%. The second frequency for Model 1.1 with full composite roof truss increased from 8.15 Hz to 9.81 Hz, up by 1.66 Hz or 20.4%. Models 1.5 to 1.7 were still more effective than other models for further enhancing the second vibration frequency by 1.05 Hz or 10.7%.

Table 7: First six in-plane modal frequencies for various models

Model	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	1.10
f_2^a (Hz)	4.29	4.34	4.35	4.36	4.56	4.56	4.56	4.36	4.36	4.36
f_2^b (Hz)	8.15	8.21	8.23	8.22	8.81	8.81	8.81	8.22	8.22	8.22
f_1^c (Hz)	5.98	6.17	6.26	6.28	6.12	6.21	6.24	6.30	6.37	6.38
f_2^c (Hz)	9.06	9.07	9.07	9.07	10.05	10.05	10.05	9.05	9.07	9.07
f_3^c (Hz)	16.79	16.85	16.91	16.93	19.07	19.22	19.23	16.89	17.07	17.09
f_4^c (Hz)	19.16	19.62	19.87	19.95	20.34	20.34	20.34	19.99	19.95	19.95
f_5^c (Hz)	37.75	37.82	37.75	37.72	40.58	40.62	40.40	37.82	37.78	37.75
f_6^c (Hz)	38.55	38.55	38.55	38.57	43.99	43.99	43.99	38.55	38.57	38.57
Change in f_2^c (%)	/	0.74	0.98	0.86	8.10	8.10	8.10	0.86	0.86	0.86
f_1^d (Hz)	6.95	7.17	7.28	7.32	7.19	7.32	7.33	7.33	7.44	7.45
f_2^d (Hz)	9.81	9.84	9.84	9.83	10.86	10.86	10.86	9.82	9.83	9.83
f_3^d (Hz)	18.58	19.49	19.55	19.57	22.35	22.36	22.36	19.52	19.74	19.82
f_4^d (Hz)	20.49	20.94	21.22	21.32	22.46	22.68	22.70	21.34	21.32	21.32
f_5^d (Hz)	38.66	38.66	38.64	38.64	44.27	44.27	44.23	38.66	38.66	38.64
f_6^d (Hz)	39.12	39.11	39.12	39.12	44.29	44.27	44.27	39.11	39.12	39.12
Change in f_2^d (%)	/	0.31	0.31	0.20	10.70	10.70	10.70	0.10	0.20	0.20

Note: [a] Bottom chord of 47 mm × 197 mm; [b] Bottom chord of 47 mm × 222 mm;
[c] Bottom chord of 47 mm × 222 mm with composite effect; [d] All truss members composite.

8 CONCLUSIONS

- This research systemically investigated the effects of roof truss bracing configuration, bottom chord size, composite bottom chord and fully composite roof truss members on the dynamic serviceability performance of the attic room floor.
- The bottom chord size was found to be the predominating factor for controlling the dynamic serviceability performance of the attic room floors.
- The addition of bracing members in the regions near the supports could largely enhance the dynamic performance of the attic room floors.
- The consideration of composite effects for the bottom chord or the whole roof truss member could largely enhance dynamic serviceability performance of the attic room floors.

REFERENCES

[1] Zhang, B., Rasmussen, B., Jorissen, A. and Harte, A. Comparison of vibrational comfort assessment criteria for design of timber floors among the European countries, *Engineering Structures* (2013), 52, 592–607.

[2] British Standard Institution. *BS EN 1995-1-1:2004+A1:2008 UK National Annex to Eurocode 5: Design of Timber Structures – Part 1-1: General - Common Rules and Rules for Buildings*, (2004), London.

[3] British Standard Institution. *NA to BS EN 1995-1-1:2004+A1:2008 UK National Annex to Eurocode 5: Design of Timber Structures – Part 1-1: General - Common Rules and Rules for Buildings*, (2009), London.

[4] Zhang, B. and Coutant, B. Dynamic performance of attic rooms in duo-pitch timber frame houses, *The World Conference on Timber Engineering – 2012 (WCTE-2012)*, (2012), *Auckland*, *New Zealand*.

[5] Computers and Structures Inc., SAP2000 Integrated finite elements analysis and design of Structures, *Tutorial Manual*, (2013), Berkeley, California, USA.

[6] British Standard Institution. *BS 5268-2 Structural Use of Timber Code of Practice for permissible Stress Design, Materials and Workmanship*, (2002), London.

[7] British Standard Institution. *BS EN 338 Structural Timber — Strength Classes*, (2009), London.