The Historic Belfast Timber Truss - A Way To Promote Sustainable Roof Construction

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Summary: Historically, timber has been used extensively for roof structures. In the 19th century demand for clear span industrial buildings brought about the development of a variety of timber truss types. The 'Belfast' truss was developed circa 1860 to meet the demand for efficient wide span industrial buildings. This is essentially a bow-string configuration with a curved top chord, straight horizontal bottom chord and close-spaced lattice bracing. It is known that several thousand still exist in Ireland, many in buildings of historic significance. Although the manufacturers claimed superior durability for the trusses, degradation has occurred mainly as a result of insect infestation and wet rotting fungi.

This paper seeks to demonstrate the efficiency of the Belfast truss and to establish that, by modern structural analysis techniques, trusses can be replicated in historic buildings almost exactly as the original. Results of a theoretical study have been compared with the behaviour of two full-scale trusses: one as a replacement truss, tested in the laboratory; the other an 80-year-old truss tested on site. In addition, experimental results from a manufacturer's archive material of full-scale truss tests carried out about 100 years ago have been compared with theoretical models. As well as their significance in historic building conservation the paper proposes that Belfast trusses are an attractive sustainable alternative to other roof structures.

Keywords: Timber, trusses, roofs, historic buildings.

1 INTRODUCTION

A booklet produced in 1930 by Anderson & Son to promote the 'Belfast' truss begins "The curved lattice girder or 'Belfast' roof, needs no introduction, having been in use for over half a century. Its advantages for the purpose of roofing wide spans, without intermediate supports, are well known." Indeed timber trusses of this type appear to have been in use from about 1866, fabricated by McTear & Co., Belfast (Gould et al. 1992). While its origin is somewhat uncertain, the efficiency of its structural behaviour was widely appreciated and the truss was employed extensively throughout Ireland and Great Britain on industrial buildings, farm buildings, airfield hangars etc. for spans ranging from 6 m to 36 m. The usage diminished around the 1930s, although farther afield it is known that trusses were regularly made in Lagos until the 1950s. Several hundred buildings with Belfast trusses are extant in Ireland; some 70 locations are known in Northern Ireland alone and the list is not exhaustive. The authors have been involved in the analysis, repair and replication of trusses on several buildings - most recently on the replacement roof of a farm building. In this case the existing trusses, severely degraded by woodworm infestation were replaced with new trusses having the same profile but a simplified internal configuration. An extra truss was fabricated for this project and tested under laboratory conditions. A larger span (12 m) truss in an existing warehouse has been tested to destruction on site. Results of ultimate load tests carried out on prototype trusses in 1906 by Andersons have been found in the company's archives. The analysis, design, fabrication and testing of trusses have resulted in a better understanding of their behaviour which is not only of historic interest and fundamental to the repair/restoration of existing trusses, but also relevant to the design of modern timber trusses and the promotion of a sustainable form of roof construction.

2 HISTORICAL BACKGROUND

Timber truss forms have been used since ancient times and enable spans that are longer than the pieces of timber available. Trusses were utilised by Palladio and Wren for major roofs, employed extensively in N.America where the material was readily available and by the beginning of the 19th century their behaviour was well understood. In the first half of that century 'king-post' and 'queen-post' trusses were widely used for industrial buildings, typically for spans to 9 m and 18 m respectively. Another truss form, the 'hammer-beam', which did not require a tie at eaves level, would have been an expensive alternative in these situations. Many of these trusses survive and are still economical to fabricate, particularly the king-post type, without the

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need for special mechanical connector devices. The 'Belfast' truss was developed to meet the demand for efficient and larger span roofs, brought about by the industrial revolution. It is no coincidence that Belfast was a centre for the production of felt, a material eminently suited as a lightweight weatherproofing membrane on the curved roofs. The Treatise by Newlands (1860) on timber construction makes no mention of the Belfast truss, so it might be assumed that the reference to the McTear truss of 1866 indicates a reasonably accurate date of origin. At the beginning of the 20th century new building types for shipbuilding and aircraft created a demand for even wider span roofs. Figure 1 shows one of the many Belfast truss roofs at the Harland and Wolff shipyard, Belfast, incidentally adjoining the slipway on which the ‘Titanic’ was later built. The photograph, taken in 1899, shows a set of trusses spanning approximately 24m supporting purlins and sarking boards. Construction of an aeroplane hangar in 1918 with a two-bay stepped roof, is illustrated in Fig. 2. In Fig. 3 a Hanley Page 'bomber' is shown outside the finished building where parallel chord steel trusses support the timber trusses over the hangar doors.

Figure 1. Harland&Wolff shipyard store 1899
(©UFTM no.H590)

Figure 2. Aeroplane hangar construction Aldergrove 1918 (©UFTM no.H2451)

3 TRUSS CONFIGURATION AND BEHAVIOUR

The general arrangement of the truss is shown in Fig. 4, consisting of a two-piece bowed top chord, a two-piece horizontal (or slightly cambered) bottom chord between which are sandwiched and nailed lattice (bracing) members. The truss profile is very efficient for uniformly distributed loading - it behaves in essence as a tied arch, with the thrust line almost coinciding with the alignment of the top chord, resulting in very small forces in the lattice members.

Various lattice layouts have been used since the trusses were first developed, all based on uniform purlin spacing along the top chord, as shown in Fig. 5 (a) to (d). It is thought that these arrangements were adopted to facilitate fabrication. For example, the pattern in Fig. 5 (d), is the most convenient to establish within a limited working area.

Figure 3. Hangar of Fig 2 as finished
(© UFTM no.455)

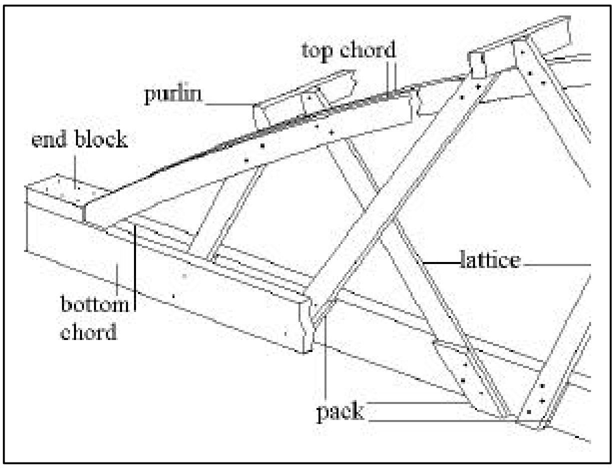

Figure 4. Belfast truss–general arrangement

The eaves joint, connecting the top and bottom chords, is the most critical detail in the truss. Figure 4 shows an 'end block' which 'stops' the horizontal component of the compression force in the top chord and transfers it as a tension force to the bottom chord. This arrangement is similar in concept to the eaves detail on a 'king' or 'queen' post truss. The block was not used on all the trusses examined and where it was present, the nail fixing to the bottom chord did not always appear to be effective.

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The trusses were made both on and off site. It is probable that the bigger trusses were made on site. Figure 6 is a good general view of Belfast trusses being fabricated - these are thought to be the same trusses shown in the hangar building of Figs. 2 and 3. It is interesting to note, that the eaves joint detail here differs from that sketched in Fig. 4. In the right foreground of Fig. 6 the lattice members form a solid gusset at the eaves joint and double members are used in the region close to the eaves. This obviously improves the load capacity of the joint and a possible reason for the double members is discussed later.

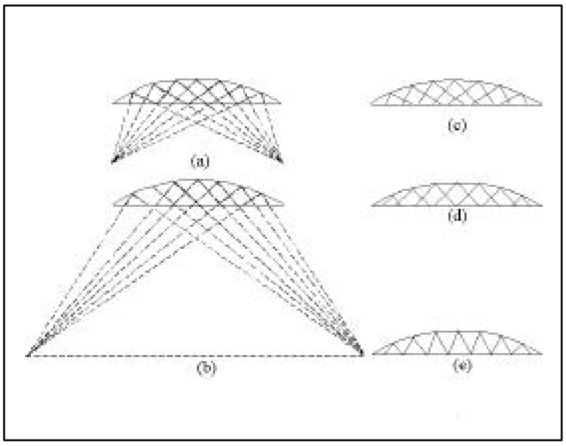

Figure 5. Variety of lattice layouts

Figure 6. Fabrication of Belfast trusses c1917
(© UFTM no.426)

4 DURABILITY ASPECTS

In all the trusses examined there appears to have been no timber treatment by creosote, solignum or the like. However, nearly all the trusses used naturally durable timber species, namely European redwood (*Pinus sylvestris*) and American pitch pine. In some trusses spruce was used for the lattice members and as a result often showed attack by beetle. The most common wood-boring insect in Ireland is the furniture beetle (*Anobium punctatum*) whose larvae together with those of other beetles, are known as 'woodworm.' This insect is responsible for most of the infestation in Irish buildings. Although damage is generally confined to sapwood, it can extend right through timber, such as spruce, within which there is no clear differentiation between sapwood and heartwood (Gilfillan and Gilbert 2001).

In relation to the felt roof finish, the Anderson Company claimed that "the original covering would last up to 40 years." This may have proved to be optimistic and there is evidence that ingress of moisture has caused 'wet rot' in some trusses, particularly at the eaves where the water was directed off the curved roof. The durability of this connection was also influenced by the type of gutter detail used. In Fig. 7(a) the gutter is located clear of the roof whereas in Fig. 7(b) it can be seen that any breakdown in the gutter lining will allow water to penetrate into the end region of the truss. The authors have designed repairs for eaves connections on two of the trusses in the aeroplane hangar roof shown in Fig. 2, in which the gutter detail is inside the building. The repairs took the form of steel splice plates to re-establish the structural connection between the top and bottom chords. The warehouse truss recently tested (truss no.3 in Table 1) was one of a set with the simple external gutter detail. None of these trusses showed any sign of degradation at the eaves detail.

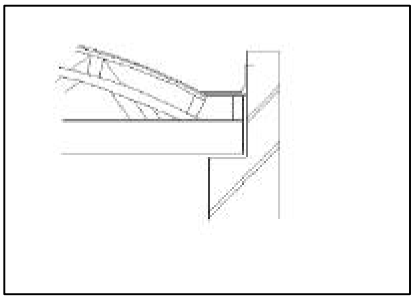

Figure 7(a). Gutter-external

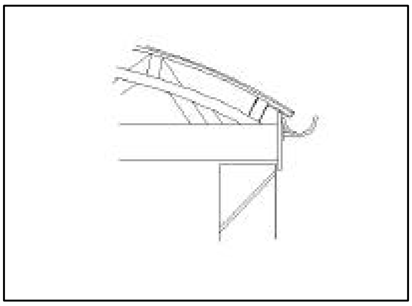

Figure 7(b). Gutter-internal

5 THEORETICAL MODELLING AND EXPERIMENTAL TESTING

Table 1 summarises the dimensions and behaviour of six trusses modelled theoretically. Three of these were subsequently tested to failure.

Modelling was carried out using a plane frame analysis software package. Two web layouts were examined for the warehouse truss, namely layouts (a) and (b) shown in Fig. 5. These are denoted as truss nos. 3 and 4 in Table 1. In fact, for the larger span trusses, it was very difficult to establish on site which web layout had been used. For each analysis the lattice members were modelled with simple pin end joints while the eaves joint was considered both pinned and fixed, the latter condition corresponding to the use of a gusset plate.

The three experimental tests have been mentioned in the introduction: truss no. 1 was a new 'bow-string' fabricated to replace truss no. 2 (the original trusses could not be tested due to severe woodworm infestation); truss no. 3 was the existing warehouse truss, tested in place using hydraulic jacks and a beam arrangement anchored to a tracked excavator; and truss no. 5 was the Anderson prototype truss for which a test report, dated 1906, was available from the company. Unfortunately, only ultimate load was recorded for the test on truss no. 5, whereas it was possible to monitor deflections in the other two tests.

Table 1. Truss dimensions, modelling and testing summary.

Truss no*	Span L(mm)	Height h(mm)	L/h	Top chord radius (mm)	Model defln. (mm)	Expt. defln. (mm)	Model failure load (kN)	Expt. failure load (kN)
1	6600	623	10.6	9060	12.7	10.8	26	23
2	6600	623	10.6	9060	12.6	-	26	-
3	12000	1300	9.2	14500	14.9	18.0	45	28
4	12000	1300	9.2	14500	14.6	-	45	-
5	11000	1200	9.2	13200	13.7	-	119	67
6	11600	1260	9.2	13980	14.4	-	91	-

* truss type/lattice layout:

1. new bow-string (Fig. 5(e))
2. truss replaced by no. 1 - 'fan' (Fig. 5(a))
3. warehouse - 'fan' (Fig. 5(a))
4. warehouse - 'right angle in semi-circle' (Fig. 5(b))
5. Anderson prototype test - 'right angle on top chord' (Fig. 5(c))
6. workshop/factory - 'right angle on bottom chord' (Fig. 5(d))

6 DISCUSSION

6.1 Truss configuration.

The Belfast truss profile is clearly efficient for uniformly distributed loading. Analysis showed that even for non-uniform loading, which might be caused by snow, the lattice forces remain relatively small. The connections of the lattice to the top and bottom chords are not subject to large forces and secondary bending due to non-concurrence at these joints is not significant.

In terms of the variety of lattice layouts outlined in Fig. 5 analysis showed that these alternatives make little or no difference to all the member forces.

The most common fabrication method produced initial lack of straightness and induced bending stresses in the lattice members. These were required to bend when crossing adjoining members because, to accommodate the lattice, the bottom chord pieces were separated by twice the member thickness and the top chord pieces by only the member thickness. The consequent lateral displacement is equivalent to half the lattice member thickness, producing a critical bending stress condition for the shorter members and a critical instability condition in the longer members. Later trusses incorporated double lattice members close to the ends, as seen in Figs.2 and 6, to compensate for the incipient weakness in the lattice.

6.2 Truss behaviour.

The top chord was undersized relative to the bottom chord for all the trusses analysed. However, it is thought that the tightly jointed sarking board (typically 16 mm thick), forming the roof deck, supplements the top chord by composite action. In addition, this curved deck may act independently as a barrel shell. There is no doubt that the sarking and purlins also prevent instability of the top chord. This was evident in the difference in the failure modes between the laboratory-based load test (truss no. 1) and the on-site tests. Thus these supplementary effects, composite action and lateral restraint, allow a smaller top chord section size, which facilitates fabrication.

Modelling predicts the presence of bending stresses in the bottom chord concentrated in the length between the eaves joint and the quarter-span point. These stresses become greater as the truss becomes more shallow. It is interesting to note that, in Table 1, all the larger span trusses have a relatively high span to height ratio of 9.2. Generally the ratio ranges from 5 to 10. The higher ratios also produce a more acute angle at the eaves, increasing the connection force there. For 'modern' bow-string trusses it is convenient to set the radius of the top chord equal to the span dimension. This results in a span/height ratio of approximately 8.

6.3 Experimental testing and theoretical modelling.

The warehouse truss (no. 3), tested in place, was slightly less stiff than predicted, as shown in Table 1. Ultimate failure was caused by slippage of the eaves joint and buckling of several lattice members close to the quarter-span position. An end part of the truss was cut out after failure and the timber, redwood chord members and spruce lattice members, was found to be in sound condition. Joint movement, especially at the eaves, could explain the reduction in stiffness.

The three pairs of trusses tested by Andersons in 1906 and observed by McKenzie and Young, Architects and Civil Engineers, all 'gave way' in the bottom chord near the quarter span position. Unfortunately, the type of failure is not reported, deflection readings are not given and the detail of the eaves joint is not illustrated. The analysis would not predict this failure. However, since the trusses were tested in pairs with the roof covering in place it may be that the behaviour was enhanced by composite action and the stabilising effect on the top chord.

Truss no. 1, laboratory tested, was one of a new set fabricated to replace existing Belfast trusses (truss no. 2). The outline of the original trusses was not changed since there was a requirement to match an existing roof in terms of span and radius. However the internal lattice, was substituted by a more conventional 'bow-string' configuration, similar to that shown in Fig. 5(e). The measured stiffness of the truss was slightly higher than that predicted. This could be explained by some fixity at the lattice member joints. The truss failed, by buckling in the top chord, at an ultimate load approximately 10% lower than predicted.

This truss was compared analytically with the original Belfast truss of the same outline. It was found that there was little difference in truss member forces except that the bow-string truss showed lower bending moments in the bottom chord and lower axial forces in the lattice members.

6.4 Fabrication and efficiency.

In terms of fabrication the bow-string truss can be compared with the Belfast truss:

(i) the lattice layout geometry is simpler;

(ii) the fabrication is easier in terms of joints - the lattice members do not cross over each other and both chords have the same separation between the pieces to accommodate the lattice members;

(iii) the lattice members are straight - there is no initial bending and incipient instability;

(iv) the detail of the eaves joint is simple and effective - a plywood gusset of the same thickness as the lattice members could be used.

In terms of efficiency it is interesting to compare these trusses with beams. Considering the case of trusses no.1 and no.2 the volume of timber used is almost the same. Nearly four times that volume of timber would be required to produce a beam with the same load carrying capacity as the trusses and such a section, approximately 350 mm deep, might need to be glue laminated.

7 CONCLUSIONS

1. The Belfast truss is a remarkably efficient structure for wide span roof construction.
2. Historically, many geometrical layouts have been used for the internal lattice members, but these variations make little difference to the truss behaviour.
3. The span to height ratio, which depends on the top chord radius used for a particular span, is the most important influence on the truss behaviour. It is recommended that the ratio should be about 8, resulting from a chord radius equal to the span dimension.
4. Experimental testing provides convincing evidence that the roof decking enhances the truss behaviour by composite action and the provision of lateral restraint to the top chord.
5. The trusses in many historic buildings have suffered from the effects of water penetration due to failure of the felt covering and leakage from the gutter. Modern high performance membranes and gutter linings will help eliminate this problem.
6. In many historic buildings the eaves connection, even in sound original condition, is inadequate. The provision of a solid boarded or plywood gusset represents a superior connection design.

7. The bow-string truss with simple lattice layout has a fabrication advantage over the traditional Belfast types. The bow-string truss is however only slightly superior in performance to the earlier types.
8. In the case of historic buildings, where the replacement of Belfast trusses is necessary, it is perfectly acceptable to replicate the original truss, subject to the provision that the eaves details may need to be altered. These are the most critical joints in the truss and a gusset-type connection may be needed to transfer the horizontal component of the top chord compression force into the bottom chord.
9. In terms of timber volume, all the trusses reviewed are considerably more efficient than equivalent beam structures. However, the superior efficiency of trusses relative to material used must be offset against higher fabrication costs. Nevertheless, these trusses can be fabricated without expensive equipment and specialist skills. The Belfast truss represents an elegant and efficient structure, which can utilise renewable, even home-grown, material economically.

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