The dynamic analysis of light aluminium/steel structures subjected to wind excitation

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Abstract

In recent years an expanding market for light skeletal structures such as walkways, shelters and large bus stations has required constructors and customers to seek information on their behaviour when subject to wind excitation.

The design of structures, taking into consideration the criteria associated with the dynamic response to wind excitation, is a specialised and highly complex task. The most significant guide for designers available at present is that produced by ESDU International plc. This is however apparently limited to particular types of structures and requires considerable interpretation in its use.

The paper reports on an examination of the dynamic response of light aluminium/steel structures, where the required dynamic analysis was carried out using the finite element method and long walkway shelters, upwards of 300m, are a particular focus. Significant idealisation of the physical problem is established and the paper presents the ‘best’ model for the analysis. The results of a parametric study are presented and combined with the wind excitation criteria, prescribed by ESDU, design curves are proposed. The finite element results are underpinned at this stage by more traditional methods of dynamic analysis, however, future experimental work is described to further validate results.

The paper concludes on the validity of the finite element modelling of the light structures and the implications of the work on design methodology.

1.0 Introduction

The last decade has seen an increasing market for light, skeletal structures such as long, covered walkways, simple bus shelters and larger bus stations constructed from extruded aluminium sections with steel section inserts riveted together. Southside Engineering Ltd. in Glasgow, Scotland, have achieved considerable success with their products.

The primary strength of most of these structures is derived from inserting a thin, steel, folded plate channel into an extruded thin, walled aluminium box section each then riveted together. A combined section gallows is shown in Fig 1.
Structures that are particularly long 200 - 300m, usually a walkway, require to be checked in regard of wind excitation. This poses a difficult problem for the design engineer who may wish to specify particular combinations of dimensions. Very long structures have to be regarded as ‘line structures’ for which natural frequencies have to be calculated and then checked with regard to the criteria presented by ESDU wind engineering code Ref 1.

Dynamic analysis of structures of this scale and nature can only be effectively carried out by finite element analysis and only beam/plate elements can be used. The steel and aluminium sections are represented by beam elements and aluminium and polycarbonate or toughened glass panels by plate elements in finite element models. This in itself becomes a problem, since for very long structures a large number of elements are required to replicate the actual structure which becomes uneconomical.

The objectives of the present research work are firstly to idealise the skeletal structures with a view to reducing the number of finite elements required to carry out a dynamics analysis. Secondly the creation of design guides for long walkways as an aid to the designer is a priority and thirdly to investigate the appropriateness of the ESDU criterion to long walkways. This paper presents the results of the research relating to the first two objectives.

2.0 Dynamic Analysis and the Engineering Problem

In this study a modal analysis is required to be performed to predict natural frequencies and mode shapes of typical structures. The criteria invoked from the ESDU design guide requires the fundamental natural frequency to be identified.

The study focuses on cantilevered gallows type walkways which can be constructed for any length without a break in the length. They also may have roof widths varying from 1m to 2m. The height of the gallows column is normally constant at 2m with a gradual rake on the roof for drainage purposes. Over its total length, a walkway will be constructed in sections (bays) - one bay is the distance between consecutive gallows; in this study the length of each bay of the walkway is 4.9 m. The roof sections are also constructed per bay length and is a fabrication of aluminium box or T-sections covered either by aluminium plate or polycarbonate sheet. Side walls are constructed from T-sections with polycarbonate or toughened glass panel inserts.

3.0 Beam/Plate Finite Element Models

The finite element software package used was the ANSYS software with pre and past processors. Typical beam/plate element models are shown in Fig 3 and Fig 4. The beam element representation of the combined aluminium box-section and the steel channel is shown in Fig 2.
The ‘coupling’ of nodes at rivet locations is achieved by using a generalised constraint which allows specification of relationships between degrees of freedom at node points and the selection of appropriate freedoms reflecting the restraining effect of the rivet.

This part of the study focused on finding an idealised structure which reduced the number of elements significantly but was accurate in the prediction of natural frequencies. Three issues were considered:

i) the need to include the side wall in the model;

ii) the reduction or idealisation of the roof section to an equivalent plate;

iii) the idealisation of the side wall to an equivalent plate.

### 3.1 Model of Complete Structure without Side Wall

Finite element models of complete structures were created one with and one without the side wall. The results presented in Table 1 show that the difference between the fundamental natural frequencies of the two structure configurations is 11.3%. This indicates that the side wall cannot be neglected in a ‘best’ idealised finite element representation.

**Table 1: Side Wall Effect**

<table>
<thead>
<tr>
<th>MODE</th>
<th>Shelter with side panel</th>
<th>Shelter with no side panel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Bay</td>
<td>2 Bay</td>
</tr>
<tr>
<td>1</td>
<td>2.518</td>
<td>2.263</td>
</tr>
<tr>
<td>2</td>
<td>4.747</td>
<td>2.543</td>
</tr>
<tr>
<td>3</td>
<td>6.514</td>
<td>5.299</td>
</tr>
<tr>
<td>4</td>
<td>11.289</td>
<td>6.028</td>
</tr>
</tbody>
</table>

### 3.2 Determination of an Equivalent Plate for Roof Sections

The roof of the walkway shelter is of hollow-box sections and T-sections in a rectangular criss-cross configuration. These are covered by 12.5mm sheet aluminium. This section is idealised as one single equivalent plate reducing the required number of finite elements from 30 to 8. Over a full-length structure upwards of 300m this leads to a significant economy in a dynamics analysis.

i) Calculation of Equivalent Roof Plate Thickness

For a rectangular plate, calculation of the thickness of the equivalent roof plate can be made by Roark’s Formula, Ref 2.

\[
\delta_{\text{max}} = \frac{-\alpha q a^4}{D} = \frac{-\alpha q a^4}{E t^3} = 12 \times \frac{-\alpha q a^4 (1 - \mu^2)}{E t^3} \]

\[
\frac{12(1 - \mu^2)}{}
\]
Where:

\( q \) = Uniformed pressure applied to the roof plate, here \( q = 100\text{N/m}^2 \) (Pa).

\( a \) = The length of the plate.

\( t \) = The thickness of the plate, here is unknown.

\( E \) = Modules of Elasticity, For aluminium \( E = 7.1\times10^{10} \).

\( \mu \) = Poisson’s ratio, for aluminium \( \mu = 0.33 \).

\( \alpha \) = Factor refer to the ratio of \( b/a \).

\( \delta_{\text{max}} \) = Maximum deflection of the plate. It can be obtained from a finite element analysis of the roof section only with \( q \) applied.

From equation (1)

\[
t = 3 \sqrt[3]{\frac{12 \times \alpha qa^4 (1 - \mu^2)}{E\delta_{\text{max}}}} = 3 \sqrt[3]{1506 \times 10^{-8} \times \frac{\alpha x a^4}{\delta_{\text{max}}}}
\]

\( \delta_{\text{max}} = 0.00298\text{m} \) at the centre of the free edge of plate from the original roof finite element analysis.

\( \alpha = 0.00515 \) of \( a \) (the length of roof) = 4.9m, \( b \) (the width of roof) = 1.9m, in the condition that the roof is treated as a plate of three edges simple supported and one edge free.

\[
t_1 = 3 \sqrt[3]{1506 \times 10^{-8} \times \frac{\alpha x a^4}{\delta_{\text{max}}}}
\]

\[
= 3 \sqrt[3]{1506 \times 10^{-8} \times 0.00515 \times 4.9^4 \frac{1}{0.00298}}
\]

\[
= 0.02466\text{m} = 24.7\text{mm}
\]

ii) Calculation of Equivalent Roof Plate Density

The density of the equivalent plate is:

\[
D = \frac{W}{V}
\]

Where: \( W = \) Mass of the original roof \( V = \) Volume of the equivalent plate

Mass of the original roof is:

\[
V_1 = a \times b \times h = 4.9 \times 1.9 \times 0.0125 = 0.1164(\text{m}^3) \text{ (aluminium sheet)}
\]
\[ V_2 = 5 \times b \times A + 3 \times a \times A = 5 \times 1.9 \times 0.000834 + 3 \times 4.9 \times 0.000834 = 0.02 (m^3) \text{ (aluminium sheet)} \]

The total volume of the original roof is:
\[ V = V_1 + V_2 = 0.1164 + 0.02 = 0.1366 (m^3) \]

Hence:
Mass = density \times volume = d \times V = 2700 \times 0.1366 = 368.8 (kg)

The volume of the equivalent plate is:
\[ V = a \times b \times t \]

Where:
\[ t = \text{ thickness of the equivalent plate.} \]
\[ a = \text{ length of the roof.} \]
\[ b = \text{ width of the roof.} \]

Hence:
\[ W = \frac{368.8}{a \times b \times t} = \frac{368.8}{4.9 \times 1.9 \times 0.0247} = 1603.8 (kg/m^3) \]

Comparison of the natural frequencies between the model with original actual roof and that with the equivalent roof plate is shown in Table 2.

**Table 2: Equivalent Roof Effect**

<table>
<thead>
<tr>
<th>MODE</th>
<th>1 Bay</th>
<th>2 Bays</th>
<th>4 Bays</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original model</td>
<td>With equivalent roof</td>
<td>Original model</td>
</tr>
<tr>
<td>1</td>
<td>2.518</td>
<td>2.515</td>
<td>2.240</td>
</tr>
<tr>
<td>2</td>
<td>4.747</td>
<td>4.920</td>
<td>3.359</td>
</tr>
<tr>
<td>4</td>
<td>11.289</td>
<td>11.230</td>
<td>6.650</td>
</tr>
</tbody>
</table>

In a similar way, the actual side wall was idealised and an equivalent plate with appropriate thickness and density determined thus making further reductions in finite element numbers.

Comparison of the natural frequencies between the actual structure model (original roof and side wall configurations) and the ‘best’ model (equivalent roof and side plate) is given in Table 3. It can be seen that extremely good results are obtained.
### Table 3: Actual Structure Versus Idealised Structure

<table>
<thead>
<tr>
<th>MODE</th>
<th>1 Bay</th>
<th>2 Bays</th>
<th>4 Bays</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original model</td>
<td>With equivalent roof &amp; side plate</td>
<td>Original model</td>
</tr>
<tr>
<td>1</td>
<td>2.518</td>
<td>2.515</td>
<td>2.240</td>
</tr>
<tr>
<td>2</td>
<td>4.747</td>
<td>4.944</td>
<td>3.359</td>
</tr>
<tr>
<td>4</td>
<td>11.289</td>
<td>11.329</td>
<td>6.650</td>
</tr>
</tbody>
</table>

### 4.0 Proposed design Guides

Having established a convenient idealised ‘best’ finite element model predicting accurate values of natural frequencies a parameter study was then undertaken to establish an aid to the design of cantilevered walkways. Varying structure length and roof width, natural frequencies were obtained from many computer runs. Fig. 5 presents the results of this study as a design guide where linear interpolation for roof widths not shown is valid, Fig 6.

### 5.0 Use of ESDU Wind Engineering Guide

The nature of the frequency of wind loading is that it mainly affects structures with low natural frequencies. The possible worst case obviously happens in situations of extreme weather conditions. Structures susceptible to wind excitation are usually extremely flexible with very low natural frequencies.

ESDU (Engineering Sciences Data Unit) Wind Engineering Ref 2 code of practice is used in this study to determine the stability of the structures under wind excitation. From the ESDU guide, the criterion for the structures susceptible to wind excitation is:

\[
\frac{f_n}{\sqrt{\xi_x}} < 30
\]

where \( \xi_x \) is the damping ratio; the damping ratio for the structures considered here selected as 0.005 in the guide and \( f_n \) is the fundamental frequency.

Thus, \( f_n \leq 2.12 \) is the critical value derived from the criterion:

\[
\frac{f_n}{\sqrt{\xi_x}} < 30.
\]

The criteria noted here is shown on Fig 6 as a line at frequency 2.12. This allows selection of structure lengths to avoid wind excitation problems. The relevance of this criterion to the type of structure under consideration requires to be investigated.
The criterion was selected on the basis of matching the walkway with the class of structure for which the criterion was established. However, the class of structure may include a broad range of structure configurations and there is thus doubt as to the appropriateness of the criterion to the walkway.

### 6.0 Proposed Experimentation

While dynamic analysis by finite elements has been well established, experimental verification of the finite element results requires to be undertaken. This, however, is envisaged as being difficult to carry out. It is possible to construct a 1 bay cantilever structure in the laboratories but the excitation and the confirmation of acceleration and deformation profiles would prove difficult and time consuming.

In the first instance a cantilever gallows will be set up and tests carried out. This will assist in confirming the validity of the corresponding finite element analysis.

### 7.0 Conclusions

Economic finite element models for the dynamic analysis of long, cantilever walkway structures constructed of aluminium/steel members have been established and shown to give excellent results.

Design curves as an aid to the designer of long walkway structures have been produced based on a study of the main parameters. They include the ESDU criterion for structures susceptible to wind excitation. Design curves based on finite element analysis can be produced for other similar type structures and is the preferred way forward.

The ESDU criterion involved herein requires to be examined as to its appropriateness for the walkway type structures focused on in this study. Experimentation is difficult and requires a clear rationalisation.

### References


Fig 1  Arrangement of Riveted Al/Steel Combined Section Gallows.

Fig 2  Beam Finite Element Representation of Combined Section Member.
Fig 3  Finite Element Model of Complete Structure.

Fig 4  Finite Element Model of Idealised Structure.
The Natural Frequencies against Length and Width of the Shelter (First Mode)

Fig 5 Design Curves for Cantilevered Structures (ESDU).

Natural Frequencies against Roof Width of the Shelter

Fig 6 Variation of Natural Frequency and Roof Width.