Dynamic response of buildings to wind loads – comparing Eurocode prEN1991-1-4 with other current UK methods

Gordon Breeze
MSc, BSc(Hons)
Senior Consultant, Centre for Structural and Geotechnical Engineering, BRE

Received: 10/03
Modified: 02/04
Accepted: 03/04
Keywords: Eurocode 1, BS 6399, Comparing, Dynamic loads, Wind, Buildings

Synopsis

This paper compares dynamic building responses calculated using the Eurocode prEN 1991-1-4 (June 2003 version), the UK Wind Loading Code of Practice (BS 6399: Part 2), and a method derived using ESDU datasheets. To make these comparisons, a notional range of UK buildings was considered, as well as several parametric buildings chosen to identify specific systematic trends. For all of these buildings, the peak base bending moment and the rms acceleration were calculated, and these values provided the basis for the theoretical comparisons. As BS 6399-2 does not predict accelerations, rms accelerations obtained using EN1991-1-4 and ESDU are compared with full-scale measurements reported in the literature.

From the theoretical study, all the methods show reasonable agreement for tall buildings in open terrain. As the building height reduces and the surroundings become more urbanised, the results show increasing variations; it is likely that these variations are caused by the different velocity profiles adopted by each method. Nevertheless, when the results are compared with full-scale building acceleration measurements, prEN 1991-1-4 and ESDU predict these accelerations reasonably well.

This work was undertaken on behalf of the Office of the Deputy Prime Minister (ODPM).

Introduction

Wind loading Codes of Practice are developed to enable the wind forces on buildings to be determined. These forces are produced by the interaction of the mean wind and gusts with the structure (usually referred to as 'static' or 'quasi-static' effects), and dynamic forces caused by the wind-induced motion of the structure. The majority of UK buildings are low-rise and sufficiently rigid that wind-induced motion effects are negligibly small; however there is a class of buildings (called 'dynamic' buildings) where such effects are significant. The taller and more slender a building, the more likely it is to behave dynamically. However, 'tallness' and/or 'slenderness' in isolation are not parameters that characterise dynamic response. The fundamental parameters affecting dynamic building motion are the mass, stiffness and damping of the structure, and the magnitude and statistical characteristics of the applied force. A consistent method of classifying 'dynamic' buildings is given by Cook[1], but this method is not straightforward, and is therefore difficult to incorporate in a codified format.

Eurocode prEN 1991-1-4[2] is a part of *Eurocode 1: Actions on Structures*, the scope of which includes all buildings and structures of height up to 200m, and includes dynamic buildings. As such, prEN 1991-1-4 encompasses two-thirds of the building height range found within the present UK Wind Loading Codes of Practice BS 6399: Part 2[3], as well as other structures (e.g. bridges, chimneys). In Annexes B and C of prEN 1991-1-4, two alternative methods (called 'Procedure 1' and 'Procedure 2') are provided that can be used to estimate building response. Results obtained using these two methods are presented here. It should be noted that the parameters recommended in prEN 1991-1-4 were used to determine results presented in this paper; in practice this document is to be used in conjunction with a UK National Annex which is presently under consideration. A number of alternative clauses are provided in this Annex which may affect the results and conclusions drawn.

This paper has been written following a study undertaken at BRE to calibrate prEN 1991-1-4 against BS 6399-2, and a method given by the Engineering Science Data Unit (ESDU). The two parameters chosen to make comparisons of building response are the peak base bending moment (PBBM) and the rms acceleration (RMSA). It is worth emphasising that the findings presented in this paper refer to dynamic buildings only. Although the prEN 1991-1-4 scope covers smaller building parts and structural elements, issues arising from the behaviour of such elements were not considered in this study.

Current UK practice

When this programme of work was started, there was no information available about the methods UK consultants and engineers most frequently used to assess or calculate wind loads on dynamic buildings. To obtain this information, a questionnaire was sent to the 50 largest UK structural consultancies, and the following conclusions were drawn:

- 7 out of 13 of the questionnaire respondents (representing UK structural engineering practices) are active in this field
- UK companies use Codes of Practice (both UK and overseas), wind tunnel testing, or consult a wind engineering expert
- UK companies do not generally use ESDU data sheets, and tend not to develop their own in-house methods.

These findings show that UK companies presently use a number of different approaches, one of which is to consult a wind engineering expert. In the UK wind engineering experts often use ESDU data sheets. Hence, despite the finding that UK companies do not directly use ESDU data sheets, comparisons were performed with the ESDU methodology for the following reasons:

- the UK lacks a consistent approach.
- UK wind engineering experts use ESDU data sheets.
- ESDU is self-consistent and has an international scientific basis.
- ESDU gives a clearly defined standard.

Approaches used and range of study

Comparing theoretical methods

When comparing results calculated using different methods, it is important to compare, as far as practicable, like-with-like. However, although individual Codes of Practice and methods are themselves self-consistent, the underlying basis of the methods (e.g. the reference wind speeds) are not the same. Hence caution needs to be exercised when 'mixing and matching' different codified values and methods. The approach adopted for the theoretical comparisons is to consider each building from the stand-point of the designer who needs to ensure that the building meets the minimum codified standards of safety, and who knows the following information:

- major building dimensions (i.e. height, cross-wind width, along-wind depth)
- building material (i.e. overall building density)

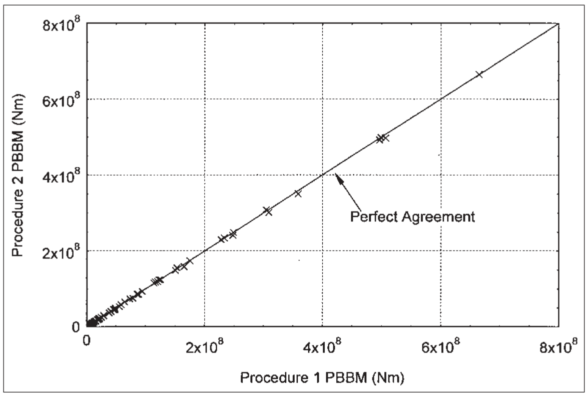


Fig 1. Behaviour of prEN 1991-1-4 procedures 1 and 2 PBBM for UK buildings

- surrounding orography and terrain surface roughness
- average height of surrounding buildings
- geographic location (i.e. altitude, latitude, distance from sea, distance from edge of town)
- return period (for UK building design purposes, this is usually taken as 50 years)
- air density.

From this information (not all of which is needed for every method), values and parameters can be obtained that enable the dynamic building response to be calculated. For the purposes of the theoretical comparisons, no other data (e.g. measured natural frequency and/or damping of the structure, mode shape, etc.) have been used; these values have been determined from the appropriate Code of Practice or method being considered. In cases where a range of values are given (e.g. the ESDU sheets give ranges of surface roughness parameters to describe wind characteristics), the value from within the range was chosen to correspond with the value given by the other methods.

As well as there being many input parameters, there are also numerous measures of the building response. In this study, two measures were chosen – the peak base bending moment (PBBM), and the rms acceleration (RMSA). The reason for these choices is that the PBBM affects directly the design of the building core and foundations, and is therefore a task undertaken at the start of the building design process. The RMSA is a useful indicator of personal comfort and perception of building movement, and there is published full-scale data that can be compared with calculated values. It should also be noted that in prEN 1991-1-4, predicted acceleration levels depend upon additional parameters to those affecting the peak base bending moment (e.g. the exponential mode shape parameter ζ has no effect upon peak base bending moment). Hence in order to test such aspects of prEN1991-1-4, predicted accelerations must form part of the investigation.

Comparing theoretical results with full-scale measurements

In the literature, there are many papers that describe full-scale measurements of dynamic building response. These measurements are usually presented in terms of the rms acceleration (RMSA) measured at a specified building height. Measurements of base bending moment were not reported in any of the published information available to the author. In many literature sources that consider dynamic building response, the results are not accompanied by appropriate wind speed information and hence such material is of no use for this study. The requirement that good quality building response measurements are taken in conjunction with wind records means that there are in fact very few appropriate literature sources.

When using results from full scale investigations important information is often missing. Furthermore, information published is often only a snapshot of all of the information collected and available for analysis. In this study, all of the information quoted in the full-scale studies was used to create, as far as possible, the most accurate documented input parameters for each of the methods used. Hence this approach is different from the approach described in the previous section, in which no additional input information was used.

The comparison with full-scale results considers only the RMSA response of the building. This means that only the prEN 1991-1-4 and ESDU methods will be compared, since BS 6399-2 does not predict building accelerations. It should be noted that to obtain the lowest building response compatible with the Codes, whenever allowed within the scope of the Codes the division by parts rules (defined in BS 6399-2 and prEN 1991-1-4) were used.

Parametric buildings

The dynamic building responses were determined for a range of buildings at specified UK locations. These locations were chosen to represent topography varying from inner city to sea-side upstream fetches, thus encompassing the full range of UK surface roughness conditions. The buildings chosen were simple prismatic blocks. These buildings all had a constant along-wind depth, with ranges of width and height; details of the buildings and site locations are given in Tables 1 and 2.

It was assumed that the buildings were made of reinforced concrete and had a slender frame structure with non load-bearing walling or cladding. These assumptions correspond with the prEN 1991-1-4 structural damping logarithmic decrement δ_s of 0.1, and a mode shape exponent ζ of 0.6. The building density was taken as 400kg/m^3, which is a typical value obtained from dynamic concrete building studies reported in the literature.

Theoretical behaviour

Comparison between prEN 1991-1-4 Procedures 1 and 2

For building heights of 20m, 40m and 80m, the nine building configurations located at eight UK sites, gives a data set of 72

Table 1: Range of building dimensions used in study

Height (m)	Cross-wind width (m)	Along-wind depth (m)
20	20, 40, 80	20
40	20, 40, 80	20
50	40	20
80	20, 40, 80	20
100	40	20
200	40	20

Table 2: Site locations and surface roughness parameters

Location	Latitude (degrees North)– used in ESDU	Environmental classification	Upstream distance from sea (km)	Upstream distance to edge of town (km)– used in BS 6399	V_s (m/s)	H_0 (m)
London City	51.5	Town	50	2	20.7	25
London Town	51.5	Town	50	2	20.7	10
Birmingham	52.6	Town	>100	2	23.0	10
Glasgow	55.8	Town	40	2	24.7	10
Scarborough	54.3	Country	1.5	0	26.5	0
Brighton	50.9	Country	0.7	0	23.1	0
Haverford West	51.8	Country	10	0	25.2	2
Sheffield	53.4	Town	100	2	29.1	10

Note that V_s and H_o are defined in BS 6399:Part 2[3].

Fig 2. (Right) Behaviour of prEN 1991-1-4 procedures 1 and 2 RMSA for UK buildings

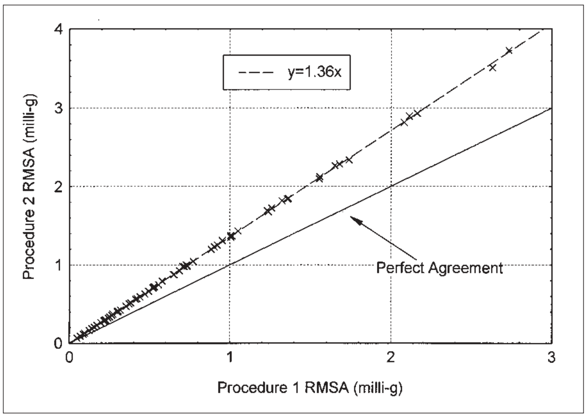
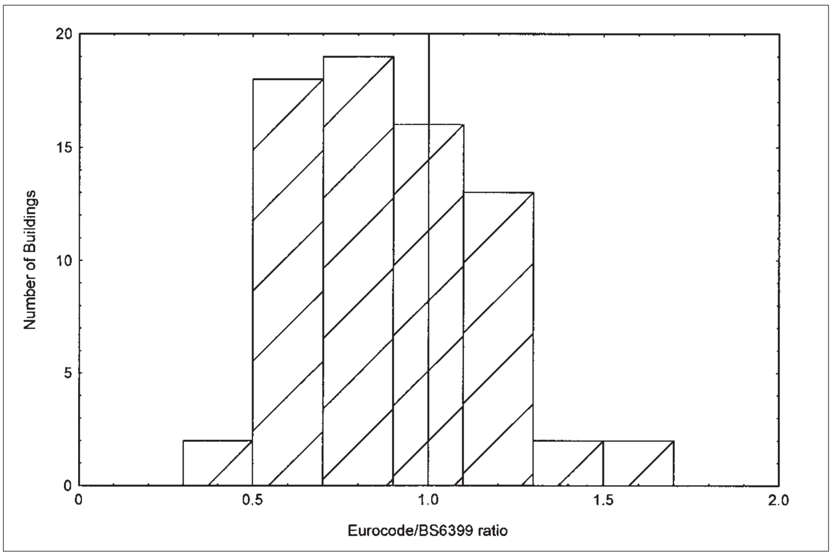


Fig 3. (Below) Probability distribution of Eurocode/BS 6399 PBBM ratios for UK buildings (total number of buildings = 72)



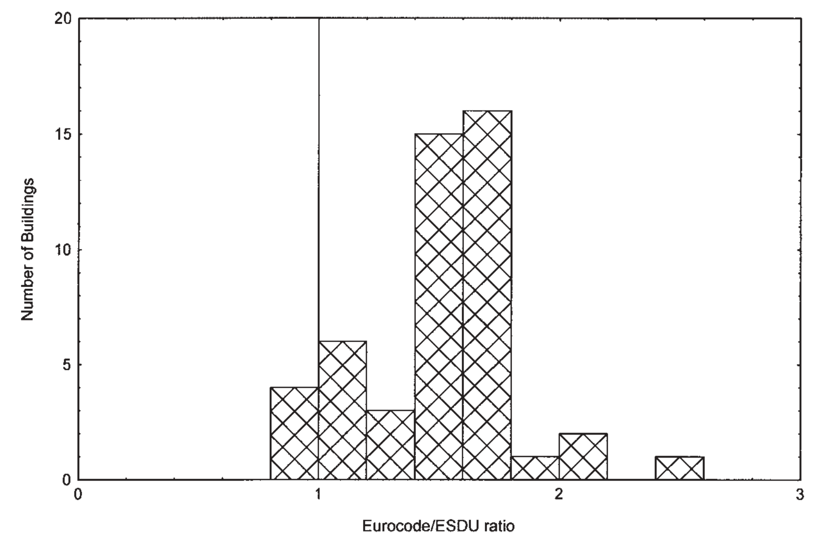


Fig 4. Probability distribution of Eurocode/ESDU PBBM ratios for UK buildings taller than 20m (total number of buildings = 48)

buildings; details of these buildings and sites are given in Annex A. For this data set, a scatter plot of the PBBM calculated by Procedure 1 and Procedure 2 is shown in Fig 1 which illustrates that the two Procedures give similar PBBMs. If the scatter plot is examined closely, it can be seen that the Procedure 1 method predicts values that, on average are slightly greater than Procedure 2. This observation is more apparent at low ratio values, which correspond with low rise urban buildings. Nevertheless, Fig 1 shows that for all practical purposes, the PBBM values predicted by Eurocode Procedures 1 and 2 are the same. A scatter plot of the RMSA acceleration results is presented in Fig 2. From the legend of this plot, it can be seen that the Procedure 2 values of RMSA predicted are about 36% greater than the Procedure 1 values.

It should be noted that in prEN 1991-1-4, Procedure 1 is the recommended method, and Procedure 2 is an alternative method. Taking the findings above into account, in the following sections of the theoretical study, only the behaviour of the prEN 1991-1-4 Procedure 1 results will be considered.

Comparison between prEN 1991-1-4, ESDU and BS 6399-2 for UK buildings

For the range of UK buildings investigated, the prEN 1991-1-4 PBBMs were divided by corresponding ESDU and BS 6399-2 PBBMs to give ratio values. The statistical variation of these ratios are shown in Fig 3 and 4, respectively. The reason for presenting ratio results in this way is that systematic differences between the two methods are shown together with the amount of scatter.

Consider firstly the Eurocode/BS 6399 ratios shown in Fig 3. They have values between about 0.4 and 1.6, distributed in a manner skewed towards ratios less than unity. The low value ratios shown correspond with low-rise buildings located in urban environments, and the high ratios correspond with tall buildings in exposed sites. Hence the skewed behaviour is a result of the fact that the majority of the UK locations are 'sub-urban' or 'town' sites. This means that on average prEN 1991-1-4 predicts lower PBBMs than BS 6399-2. However the results presented show that the loads predicted can be less than half the BS 6399-2 values (indeed, the worst-case ratio is not calculated, since only the range of buildings stated in Tables 1 and 2 were considered), and this raises obvious safety issues. The buildings where these low prEN 1991-1-4 values occur are low rise buildings in urban environments. However, for tall buildings in open-site locations, prEN 1991-1-4 is likely to predict larger loads than BS 6399-2. In this situation, using prEN 1991-1-4 instead of BS 6399-2 will incur an economic penalty.

The expressions given in ESDU data sheets do not predict realistic forces acting on 20m tall buildings in the London City location. This is because the theoretical velocity profile expressions predict zero velocity at a height known as the zero plane displacement height; for city locations, this displacement height can be a significant proportion of the building height. Since ESDU does not give information for windspeeds below the zero plane displacement height, the aerodynamic forces derived from these winds cannot be calculated. As a result, none of the 20m UK building PBBM ratios are considered in the results shown in Fig 4. Hence the number of combinations of buildings and locations considered in this reduced sample is 48 (six buildings, eight locations).

The variation of the Eurocode/ESDU PBBM ratio results are presented in Fig 4. It can be seen that the ratios vary between about 0.8 and 2.6, with most of the ratios being concentrated around 1.6. For these results, the lower PBBM Eurocode/ESDU ratios correspond with tall buildings in exposed sites and the higher ratios correspond with low buildings in urban environments; hence this is the opposite of the Eurocode/BS 6399 ratio behaviour. This means that using prEN1991-4 instead of the ESDU method is likely to incur an economic penalty.

The Eurocode/ESDU RMSA ratio distribution is shown plotted in Fig 5 and it can be seen that the ratios range between 1 and 18, with most lying between 1 and 4. The outlying point having a ratio value of 18 corresponds with the shortest widest building considered in London City. Although it might seem that this large variation of RMSA Eurocode/ESDU ratio is significant, for practical codification purposes this is not necessarily important. This is because the RMSA ratios are generally greater than unity, and hence prEN 1991-1-4 is likely to be conservative. The large Eurocode/ESDU RMSA ratio values calculated correspond with buildings that have very low RMSA response. Indeed, for the particular building having the largest ratio, for a 50 year return period wind, the RMSA response predicted by ESDU and prEN 1991-1-4 are 0.008 and 0.188milli-g, respectively. When these RMSA values are considered in light of the fact that a value of less than 5milli-g is commonly regarded as being imperceptible, it can be seen that such low levels of RMSA predicted by pr EN 1991-1-4 do not constitute a concern for the building designer.

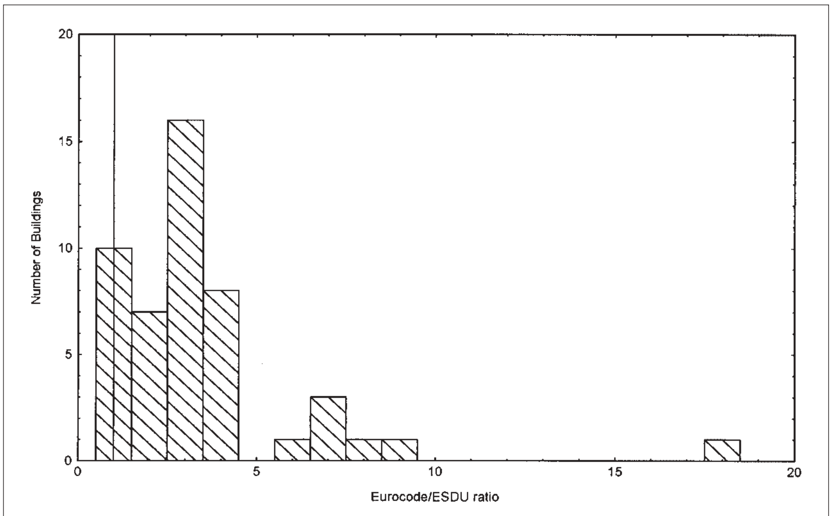


Fig 5. Probability distribution of Eurocode/ESDU RMSA ratios for UK buildings taller than 20m (total number of buildings = 48)

Effect of building height and construction

The effect of building height and construction was studied by comparing the results for buildings in London City and Scarborough; these locations represent the most sheltered and most exposed sites respectively. Considering firstly the Eurocode/BS 6399 PBBM ratio behaviour, the results are presented in Fig 6. This figure shows clearly that, although there is scatter in the results, the Eurocode/BS 6399 ratio increases as a function of building height. It can also be seen that the Scarborough results are systematically higher than the London City results, which is consistent with the results noted previously. These findings also mirror the trends that were obtained in a calibration study of chimney response using prEN1991-1-4[4].

The Eurocode/ESDU PBBM ratios for Scarborough and London City are plotted as a function of building height in Fig 7. It can be seen that for Scarborough, there is very good general agreement between ESDU and prEN 1991-1-4. However, for London City, the ratios are always significantly greater than unity (again this trend corresponds with the behaviour noted previously). It can also be seen that for London City the PBBM ratios appear to show a height dependence, with the ratios increasing

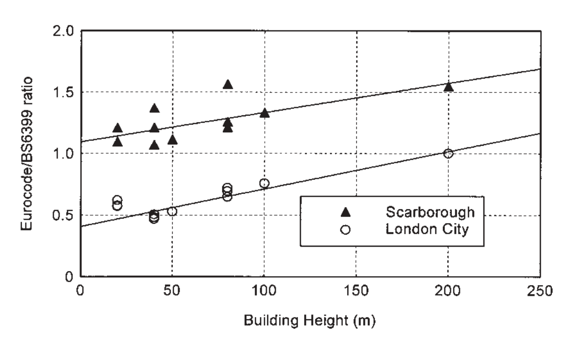


Fig 6.
Effect of building height upon Eurocode/BS6399 PBBM ratios

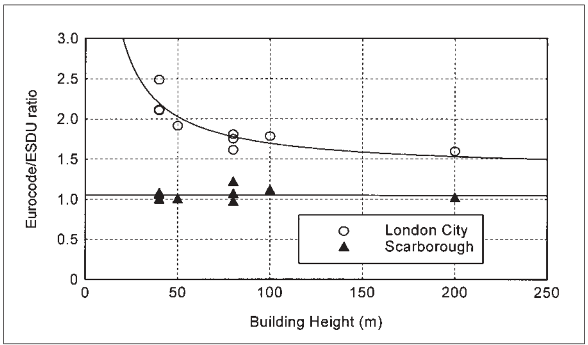


Fig 7.
Effect of building height upon Eurocode/ESDU PBBM ratios

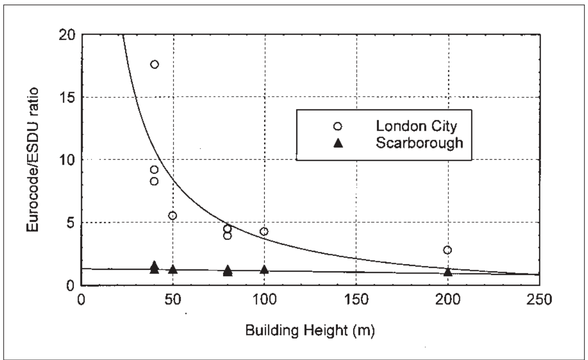


Fig 8.
Effect of building height upon Eurocode/ESDU RMSA ratios

as building height reduces.

The RMSA Eurocode/ESDU ratios for Scarborough and London City are plotted as a function of building height in Fig 8 and the trends shown are similar to those in Fig 7. For the Scarborough site, the results obtained using the two methods show very good agreement over the whole height range. However, for the London City site, the results show large differences that increase rapidly as building height reduces. This trend is consistent with the comments about the lowest widest building RMSA ratio behaviour made previously.

The results presented in this study show that the PBBM and RMSA ratios (calculated using prEN 1001-1-4 and the BS 6399-2 and ESDU approaches) show dependencies upon height and surface terrain. Many building-related parameters are the same for each method considered, but the equations used to determine the variation of windspeed with height differs for each of the three approaches. This suggests that these dependencies are probably caused by systematic differences in the velocity profiles.

An investigation of the effect that building material type has upon the building response was undertaken as a part of this study. For Scarborough and London City, the reinforced concrete buildings in Tables 1 & 2 were re-analysed as if they were mixed structures of concrete and steel (density 133kg/m^3, $\delta_s = 0.08$). The mode shape parameter ζ was also varied between 0.6 and 1.5. It was found that compared with the BS 6399-2 and ESDU methods, the PBBM ratios were insensitive to both of these parameters. When the Eurocode/ESDU RMSA ratios* were considered, small systematic variations with building material were observed. However, the RMSA ratios were affected in a significant way by changes to the mode shape parameter. The largest effects occurred for the London City site, and increasing this parameter reduced the RMSA ratio, tending to bring the prEN 1991-1-4 RMSA values nearer to the ESDU predictions.

*Note again that BS 6399-2 does not predict accelerations.

Comparison with full-scale measurements

Hume Point, London (height = 66.9m)

Of all the full-scale buildings considered, the published information available from Hume Point is by far the most comprehensive; details about the building, the measurement method and equipment, and the results obtained can be found[5-9]. Hume Point was a 23-storey reinforced concrete building (major dimensions 66.9 × 23.7 × 17.9m) located in London. The surrounding buildings consisted mainly of 2-3 storey buildings. The site was flat and there was no significant orography.

For west and south winds, the RMSA measurements taken are presented in Fig 9 and Fig 10, along with predicted values from prEN 1991-1-4 and ESDU. For westerly winds, it can be seen that there is remarkably good agreement between the measured results and the prEN 1991-1-4 Procedure 1 method. It can also be seen that the Procedure 2 method tends to over-predict the measured accelerations (which is conservative), whereas the ESDU method under-predicts the RMSA values. A similar trend is observed for south winds, but in this situation, the measured results fall between the prEN 1991-1-4 and ESDU predictions. Note that for this south wind direction, the prEN 1991-1-4 Procedure 1 predicts slightly conservative RMSA behaviour, with larger values still being predicted by Procedure 2.

Commerce Court West, Toronto (height = 239m)

Commerce Court West a steel-framed 57-storey tower located in Toronto, Canada, information about which was obtained from ref. 10. To the east of the site is unobstructed urban terrain. The major dimensions of the regular rectangular building are 239 × 69.7 × 36.5m. Since prEN 1991-1-4 considers only buildings up to 200m in height, this building falls outside the scope of the Code. Nevertheless, the dearth of good quality full-scale measured data means that one cannot be too choosy about making such comparisons, provided appropriate caveats are made.

The orientation of the building is such that the largest plan dimensions are perpendicular to easterly and westerly winds. Although full-scale measurements are presented for all wind

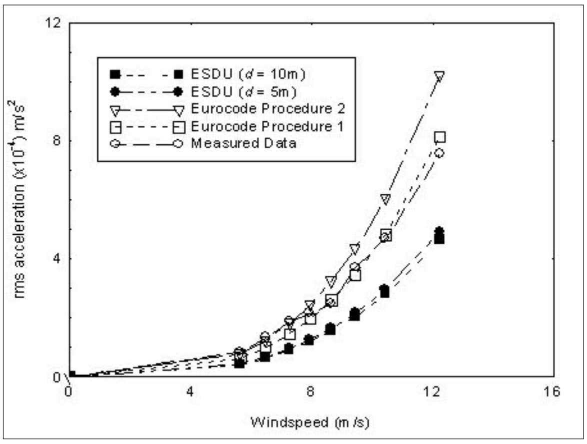


Fig 9.
Comparison between Hume Point measured and predicted RMSA: West wind building response

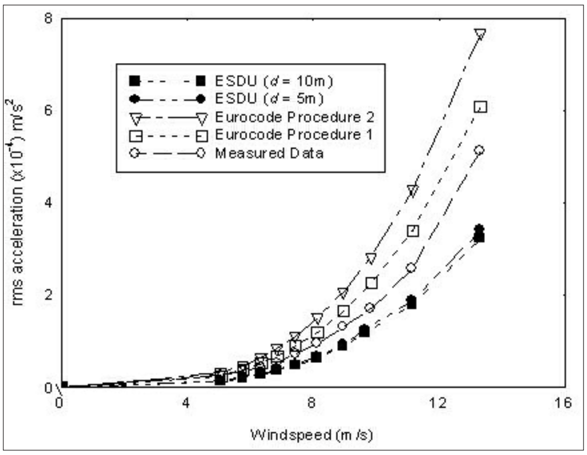


Fig 10.
Comparison between Hume Point measured and predicted RMSA: South wind building response

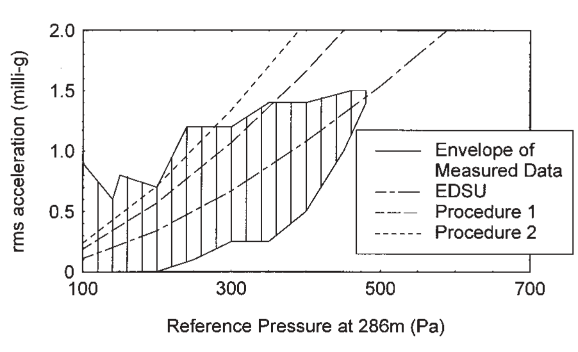


Fig 11. Comparison between measured and predicted accelerations of Commerce Court West

directions, the complex nature of the site means that it is appropriate to compare values predicted by prEN 1991-1-4 and ESDU only with the unobstructed easterly wind results.

The dynamic building response of Commerce Court West subjected to easterly winds is shown in Fig 11. The predicted results are shown together with an enclosed region that represents the outermost boundary of the full-scale measurements presented in the literature[10]. The general trends of these measurements is that RMSA increases with wind speed (or reference pressure). Overall, it can be seen that all the methods used predict the RMSA values reasonably well. An examination of the predicted responses obtained using the individual methods shows that the ESDU/RMSA values are less than the prEN 1991-1-4 results, and the procedure 1 values are less in turn than the Procedure 2 results. From Fig 11, for a given wind speed it can be seen that the ESDU method predicts the centre of the scatter of the measured data, whilst the prEN 1991-1-4 Procedure 2 tends to predict the largest measured RMSA values.

Hancock Tower, Chicago (height = 337.4m)

The Hancock Tower is a 100-storey steel framed building located in the centre of Chicago, USA, for which ref. 11 supplied the information. An interesting feature is that it tapers towards the top. Whereas the ESDU method takes taper effects into account, there is no corresponding provision in prEN 1991-1-4. Hence for the purposes of comparison with prEN 1991-1-4, the average building width and depth was taken to determine the building response. The major dimensions of the tower are height = 337.4m, plan dimensions at base 50.3 × 80.8m, plan dimensions at top 30.5×48.8m. Since prEN 1991-1-4 only considers buildings up to 200m in height, this building clearly falls outside the scope of prEN 1991-1-4. However, the paucity of good quality full-scale data means that predictions from both of these methods have been used to compare with the full-scale measured results.

The response of the building was measured in westerly winds, and for these winds the upstream fetch is described as 'urban'. When the wind blew from this direction, the building was oriented so that its smaller walls faced this approaching wind direction. In ref. 11 the dynamic response of the tower is presented as the rms resonant deflection (in inches), and therefore to make a comparison with these results, the prEN 1991-1-4 and ESDU RMSA values (in milli-g) needed to be converted.

The comparison between the measured and predicted response of John Hancock Tower are shown on Fig 12. In general, all three methods show good agreement with the measured data. The largest responses are predicted by the ESDU method, and the prEN 1991-1-4 Procedure 2 predicts values that are larger than those values predicted by Procedure 1. The observation that the ESDU method predicts a higher dynamic response for this particular building, as compared with a predicted lower response for all of the other full scale buildings is interesting, and is discussed further in a later section. For the higher wind speeds, it can be seen that all of the methods predict slightly conservative building response.

Discussion of full-scale comparisons

The results presented in this paper show the accelerations predicted by ESDU and by prEN 1991-1-4 predict the measured RMSA response of the buildings reasonably well. For these buildings (and in the theoretical studies noted in the previous section), the predicted response of prEN 1991-1-4 Procedure 2 is always greater than Procedure 1. For a given building, it appears that the value of along-wind drag coefficient is the most important parameter that determines whether the ESDU values of dynamic response are higher or lower than the prEN 1991-1-4 values; the larger the drag coefficient, the greater the predicted dynamic building response. Note that for the same building geometry different values of drag coefficient are given by each method. Therefore the finding that dynamic building response is sensitive to this parameter emphasises the general principle that care must be taken when 'mixing and matching' such parameters from different sources.

An exception to these findings was the behaviour of Haneda Airport Tower[12,13], for which, the predictions of the response using all three methods were significantly lower (as low as 38%) than the full-scale measured results. It is interesting to note that because of its unusual geometry gross simplifications of the tower shape were made, and the fact that both the ESDU and prEN 1991-1-4 predicts significantly lower responses suggests that the same assumption might be the cause of this disagreement.

It would be convenient to be able to 'sweep under the carpet' the Haneda Airport tower results, and reject them as being caused simply by large assumptions about the building shape and its adjacent large buildings. However, such an action could be overly hasty since there is nothing in prEN 1991-1-4 or ESDU that precludes such a building from their scope. If the full-scale results are correct, this suggests that this tower could experience more than double the rms accelerations predicted.

The evidence presented in this paper suggests that the large levels of disagreement obtained when comparing the Haneda Airport tower results is unusual when compared to the other buildings. The reasons for the significant discrepancies in the results observed are not presently fully understood. However, this does not prevent one from stating that the prEN 1991-1-4 and ESDU methods generally predict the full-scale RMSA dynamic building response reasonably accurately.

Conclusions

It should be noted that the parameters recommended in prEN 1991-1-4 were used to determine results presented in this paper; in practice this document is to be used in conjunction with a UK National Annex which is presently under development. A number of alternative clauses are provided in this Annex which may affect the results and conclusions drawn in this paper.

Peak base bending moment (PBBM)

For practical purposes, the PBBMs predicted by prEN 1991-1-4 Procedures 1 and 2 can be taken to be the same.

Taking into account the overall behaviour of the buildings considered in this study, on average prEN 1991-1-4 predicts lower PBBMs than BS 6399-2. For the range of buildings studied, the lowest value was 45% of the BS 6399-2 value. Hence if the BS 6399-2 values are correct, adopting the prEN 1991-1-4 for UK

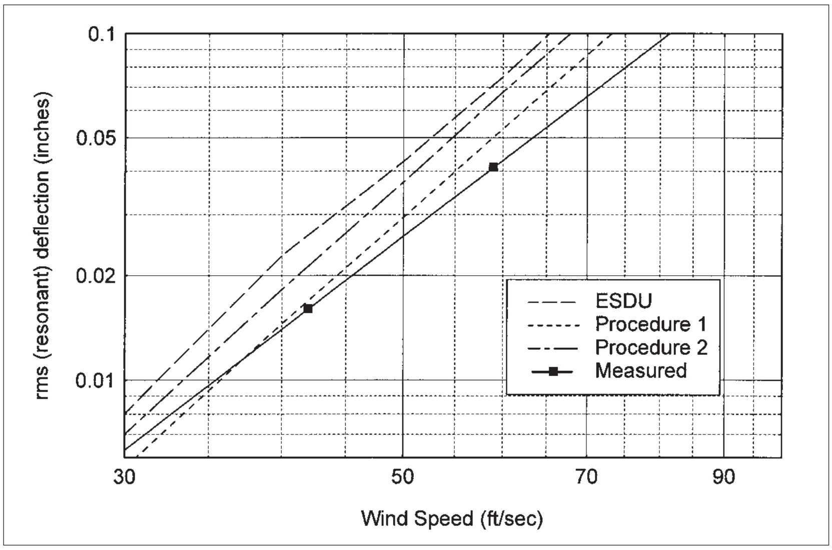


Fig 12. Comparison between measured and predicted accelerations of Hancock Tower

applications probably has safety implications. These low loads generally occur for low-rise buildings in urban areas. For high-rise buildings in exposed sites, prEN 1991-1-4 predicts slightly larger PBBMs than BS 6399-2, which may therefore have economic penalties.

For tall buildings in exposed terrain, prEN 1991-1-4 shows very good agreement with PBBM values predicted by ESDU. However, as building height reduces, and the terrain becomes more urban in nature, prEN 1991-1-4 predicts increasingly larger PBBMs than ESDU; for the range of buildings studied, the largest value was almost two and a half times the ESDU value.

There is evidence that differences between the PBBM values predicted by prEN 1991-1-4 , and values predicted by BS 6399-2 and ESDU are caused by differences in the mean wind velocity profile.

rms accelerations (RMSA)

For the parametric buildings studied, prEN 1991-1-4 predicts larger RMSA values than the ESDU method. It is thought that the most likely reason for this behaviour is caused by differences in the mean wind velocity profile. Changes of the building mass and damping appear to have little influence upon this behaviour. However, changes of the mode shape exponent can cause significant changes, especially in urban surroundings.

For full-scale buildings, it appears that the value of along-wind drag coefficient is the most important parameter that determines whether the ESDU values of dynamic response are higher or lower than the prEN 1991-1-4 values.

The prEN 1991-1-4 Procedure 2 predicts RMSA values about 36% larger than Procedure 1. This behaviour was observed both for the parametric range of buildings, and for the full-scale buildings studied.

In general, both ESDU and prEN 1991-1-4 predict RMSA values that agree reasonably well with full-scale published information.

Acknowledgments

This work was undertaken on behalf of the Office of the Deputy Prime Minister (ODPM).

REFERENCES

1. Cook, N. J.: *The designer's guide to wind loading of structures. Part 1: Background, damage survey, wind data and structural classification.* Butterworths, 1985. ISBN 0 408 00870 9
2. prEN 1991-1-4.6 June 2003. Eurocode 1: *Actions on Structures – Part 1-4: General actions – Wind actions*
3. British Standard BS 6399-2: 1997 *Incorporating amendment 1. Loading for Buildings – Part 2: Code of Practice for wind loads.* ISBN 0 580 27447 0. BSI, 1997
4. Freathy, P. F.: 'Calibration of prEN 1991-1-4 for the wind loading of industrial chimneys'. *Anemos Associates Ltd Report. Private Communication.* September 2002. The main findings of this report are documented in *Proc. 5th UK Conf. on Wind Engineering*, University of Nottingham, September 2002
5. Ellis, B. R. and Littler, J. D.: *Dynamic response of nine similar tower blocks. JWIA 28*, 1988, Elsevier
6. Littler, J. D. and Ellis, B. R.: *Interim findings from full-scale measurements at Hume Point. JWIA 36*, 1990, Elsevier
7. Littler, J. D.: 'The response of a tall building to wind loading'. PhD thesis, University College, London, March 1991
8. Littler, J. D. and Ellis B. R.: *Full-scale measurements to determine the response of Hume Point to wind loading. JWIA 41-44*, 1992, Elsevier
9. Littler, J. D. and Murphy, P. D.: *A comparison between the full-scale measured response of Hume Point and that calculated by some predictive methods. JWIA 52*, 1994, Elsevier.
10. Dalgleish, W. A., Cooper, K. R. and Templin, J. T.: *Comparison of model and full-scale accelerations of a high rise building. JWIA 13*, 1983, Elsevier
11. Davenport, A. G., Hogan, M. and Vickery, B. J. 'An analysis of records of wind induced building motion and column strain taken at the John Hancock Center (Chicago)'. *Report BLWT-10-1970.* University of Western Ontario, London, Canada
12. Tamura, Y., Kousaka, R. and Modi, V. J.: *Practical application of nutation damper for suppressing wind-induced vibrations of airport towers. JWIA 41-44*, 1992, Elsevier
13. Tamura, Y. : *Wind-induced responses of an airport tower – efficiency of tuned liquid damper. JWIA 65*, 1996, Elsevier

Notices & Proceedings

ORDINARY GENERAL MEETING

An Ordinary General Meeting of the Institution of Structural Engineers was held at 11 Upper Belgrave Street, London SW1X 8BH on 27 May 2004 with Professor David A Nethercot FREng PhD DSc BSc(Eng) CEng FIStructE FICE FCGI in the chair. The following were elected in accordance with the Bye-Laws:

ELECTIONS:
Students (78)

Graduates (139)

Members (2)
BYFIELD, Michael Patrick
USMANI, Asif Sohail

TRANSFERS:
Students to Graduates (66)

Graduates to Members (2)
CHAN, Ho Yin
CLOUGH, Robert Allan

Members to Fellows (7)
BURGOYNE, Christopher John
FLETCHER, David George
KINDREGAN, Joseph Anthony
LAM, Dennis
LIU, Sik Wing
NARASIMHARAJAN, Sharma
PETERS, Jeremy Hugh

READMISSIONS:
Students (56)

Graduates (5)

Members (4)
DUNN Peter, Cheshire
HO Wai Kuen,
O'SULLIVAN John Vincent,
TANG Ka Wah Donnie,

NOTICE:
Resignations
Council has accepted, with regret, the following resignations:

As at 31 December 2003:
Students (9)

Graduates (6)

Associate-Members (1)
HOOI, Kam Chiew

Members (13)
AU, Yiu Ting
BEIRNE, Terence
BOYNTON, Roger Anthony
BROUGHTON, Kenneth Henry
CHOI, Kin Keung
EAST, Robert William
FRANCIS, Roy
FUNG, Chi Fai
HASLEM, Robert Frank
KNOTT, John Duncan
SPENCER, Norris
TURNER, Peter Stanley
WATSON-JONES, Robert Donald

Fellows (3)
ARNETT, John Arthur
CASSON, Jeffrey Paul
FALLON, Andrew Ross

As at 31 December 2004:
Students (5)

Graduates (1)

Members (5)
CHAKRABARTI, Subhash
CLARK, Eric Davies
MORRIS, Colin Clive
ROUTLEDGE, David Anthony
SMITH, Barry

Deaths
After particularly noting the death of Kenneth Severn, Past President, the deaths of the following are reported with regret:

Members (16)
BUSHELL, Ronald Austin
CANNELL, Andrew Peter
CLARK, Michael William
FENNER, Raymond Michael
FRY, Gerald John
JANDO, Piara Singh
JOHNSON, Eric
KETTLEWELL, Derek Harold
LEWIS, Denys Hamilton
MALE, Edwin Talbot
MCQUIRE, Gordon Eric
PEDERSEN, Peter Raymond
STEDMAN, Michael John
WEST, Dennis Jeseph
WHITAKER, Eric Cardale
WILDSMITH, Alan Leslie

Fellows (5)
DOWDESWELL, John Garnet
GIRI, Gourdas
GREENFIELD, Frederick Charles
MEINHARDT, William Lindsay
SEVERN, Kenneth

The information in the minutes and this notice should be referred to when consulting the Institution's Sessional Yearbook & Directory of Members. The Institution will confirm, on request, the current membership status of any individual.