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In this issue

Multi-wavelength sized finite elements for wave scattering problems in the frequency domain

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Introduction

The Finite Element Method (FEM) has been used for many years for the solution of wave problems. To ensure accurate simulation, each wavelength is discretised into around ten nodal points with the finite element mesh being updated for each frequency to ensure adequate resolution of the wave pattern. This technique works well when the wavelength is long or the model domain is small. However, when the converse applies and the wavelength is small or the domain of interest is large, the finite element mesh requires a large number of elements, and the procedure becomes computationally expensive and impractical. Moreover, at high frequencies, the pollution error reduces further the accuracy of the results and further refinement is required to achieve satisfactory results. This is the case for many problems of practical interest; such as propagation of noise through the air, traffic vibrations from roads and railways, seismic induced vibrations and foundation construction. The aim of the proposed work is to accurately model wave problems with fewer elements, capable of containing many wavelengths per nodal spacing, and without refining the mesh at each frequency. Therefore we seek a new method in which the discretisation of the domain is more economical.

In the last decade, significant efforts have been made on the simulation of high frequency wave problems to address various issues in engineering applications (see, for example, [1]). A promising idea to tackle this issue is to incorporate the physical features of the solution into the finite element space and use relatively coarse mesh grids, in which each element may contain many wavelengths.

This approach has been adopted for Helmholtz problems, in acoustics and surface water waves, by locally approximating the solution as a superposition of propagating plane waves or by enriching the polynomial finite element space with the plane waves. Theses methods include mainly the Partition of Unity Finite Element Method

(PUFEM) [2], the generalized finite element method [3] and the Discontinuous Enrichment Method (DEM) [4]. In the PUFEM, the polynomial finite element basis is multiplied by plane waves whereas, in the DEM, the plane waves are added to the polynomial basis. A purely plane wave approximation was used in the Ultra Weak Variational Formulation (UWVF) [5] and in the least-squares method [6]. Other solutions were also considered such as the oscillated finite element polynomials [7].

In the framework of time harmonic elastic wave problems, the plane wave decomposition by P and S plane waves, was successfully implemented for the two-dimensional problem, using the Partition of Unity Boundary Element Method (PUBEM) [8], the UWVF method [9], the DEM [10], and more recently via the PUFEM [11].

Here, the PUFEM is first presented for the modelling of surface water waves governed by the Helmholtz equation and then for elastic wave problems, in two dimensions. Numerical experiments dealing with wave scattering are carried out and a comparison between PUFEM and FEM is presented. In summary, the PUFEM allows the simulation of acoustic and elastic wave problems with finite elements containing many wavelengths per nodal spacing rather than with many elements per wavelength usually adopted with standard polynomial based finite elements.

Surface water wave modelling

We consider wave problems governed by the Helmholtz equation expressed in terms of the scalar potential ϕ in a domain Ω bounded by Γ. This describes, for example, surface water waves in a medium with constant depth. The problem is defined by

$$(\nabla^2 + k^2)\phi = 0 \qquad \text{in} \quad \Omega, \tag{1}$$

where ∇^2 denotes the Laplacian operator and k is the wave number. The time variable is removed by considering a harmonic steady state. Robin boundary conditions are specified on the boundary Γ. These are

$$\nabla\phi \cdot \boldsymbol{n} + \mathrm{i}k\phi = g \qquad \text{on} \quad \Gamma, \tag{2}$$

where g is the boundary condition, ∇ is the gradient vector operator, $\boldsymbol{n}$ is the outward normal to the line boundary Γ and i is the imaginary unit such that $\mathrm{i} = \sqrt{-1}$. At this level, it is important to mention that the Robin boundary condition is used so that known analytical solutions could be imposed on the boundary of the domain to avoid numerical errors due to the approximation of the artificial boundary condition because we are mainly interested in the validation of the numerical model.

The differential equation (1) is multiplied by an arbitrary weight function ψ and then integrated by parts to give the weak form

$$\int_\Omega \left(\nabla\psi \cdot \nabla\phi - k^2\psi\phi\right)\, d\Omega \;+\; \mathrm{i}k \int_\Gamma \psi\phi \, d\Gamma = \int_\Gamma \psi g \, d\Gamma. \tag{3}$$

The computational domain is divided into n-noded finite elements. Within each finite element, the potential is first written as a polynomial interpolation of the nodal values of the potential. Then each nodal potential is approximated by a discrete sum of plane waves propagating in different directions in the plane. The unknowns are no longer the nodal values of the potential but are now the amplitudes attached to each node with respect to each direction of the chosen plane waves. In our case, a number m_j of plane waves are used in the approximating system at the node j which reads as follow

$$\phi = \sum_{j=1}^{n}\sum_{l=1}^{m_j} N_j \exp\left(\mathrm{i}k\boldsymbol{\xi}_l \cdot \boldsymbol{r}\right) A_j^l, \tag{4}$$

where N_j is a polynomial shape function, $\boldsymbol{r}$ is the radius vector, and A_j^l is the amplitude at node j with respect to the direction θ_l.

The number of approximating plane waves may vary from one node to another. Their chosen directions could be evenly spaced or clustered around directions of preference. Though there is no restriction concerning the directions $\boldsymbol{\xi}_l$, these are taken to be evenly distributed on the unit circle,

$$\boldsymbol{\xi}_l = \left(\cos\theta_l, \sin\theta_l\right) \quad \text{with} \quad \theta_l = 2\pi l/m_j, \tag{5}$$

The problem (3) leads to an invertible linear algebraic system

$$\mathbf{WA} = \mathbf{B}, \tag{6}$$

provided that the plane wave finite element components involved in (4) spanning the plane are linearly independent. $\mathbf{W}$ is a Hermitian matrix, $\mathbf{A}$ is the unknown amplitudes vector and $\mathbf{B}$ is the second member. The integrals of expressions (3) are carried out by using high order Gauss-Legendre scheme which is necessary because of the oscillatory behaviour of the integrand. The number of integration points depends on the number of wavelengths contained per nodal spacing. The solution of the linear system (6) is obtained by the use of a direct solver without any pretreatment of the global matrix $\mathbf{W}$.

To validate the proposed method, multiple scattering examples are considered. In such problems a plane wave travelling along the horizontal axis from left to right, hits an array of cylinders. The diffracted wave by one cylinder hits the other scatterers to diffract again and so on. If the scatterers are far enough from each other this interaction could be neglected. Otherwise, all the scatterers should be studied as one system.

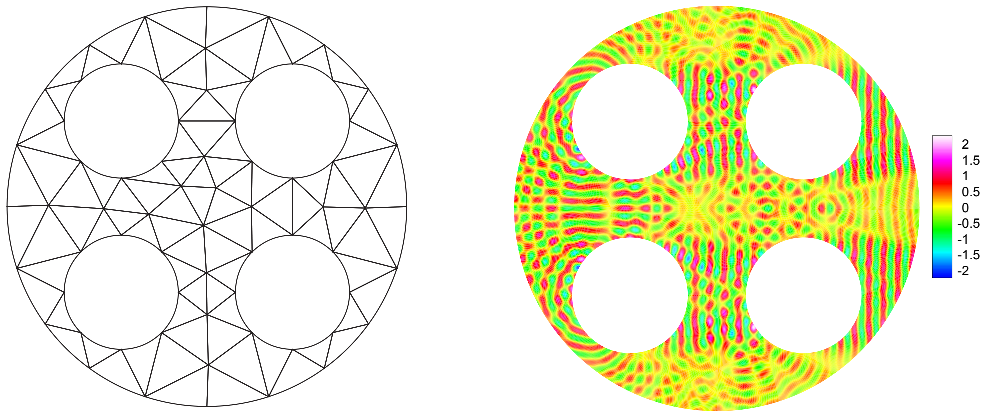

Figure 1: Multiple scattering problem, $N = 4$, $ka = 8\pi$, $\tau = 3.61$, $\epsilon_2 = 0.47\%$.

N	$ka = 6\pi$		$ka = 8\pi$	
	τ	$\epsilon_2[\%]$	τ	$\epsilon_2[\%]$
4	4.17	0.36	3.61	0.47
5	4.36	0.32	3.78	0.33
8	4.03	0.73	3.49	0.88
9	4.07	0.34	3.52	0.85

Table 1: Multiple scattering problem for $ka = 6\pi$ and $ka = 8\pi$.

For illustration purpose, an example of a wave diffraction by an array of 4 cylinders, of radii a taken equal to a unit of length, is shown in Figure 1. The problem is solved for $ka = 8\pi$, which leads to a wavelength $\lambda/a = 0.25$, with a set of 24 plane waves attached at each nodal point. Figure 1 shows the mesh grid of the computational domain and the real part of the diffracted potential. The L_2-norm error $\epsilon_2 = 0.47\%$, which is determined by comparing the numerical solution to the analytical solution of the problem, indicates the good quality of the results for a discretisation level of 3.61 degrees of freedom per wavelength.

Four different configurations are dealt with, in which the number N of diffracting cylinder is taken equal to 4, 5, 8 and 9. The problems are solved for $ka = 6\pi$ and $ka = 8\pi$ with the same set of 24 evenly spaced plane waves. The number of integration points is adjusted for each configuration depending on the number of wavelengths per nodal spacing. Here, quadratic interpolation is used to describe the circular geometry of the outer boundary and the boundaries of the diffracting cylinders. Table 1 shows the L_2 error ϵ_2 in % and the number τ of degrees of freedom per wavelength for each test problem. In all cases, the error in less than 1% with a low discretisation level compared to standard polynomial finite elements which requires $\tau = 10$. It is clear from the shown mesh grid of Figure 1 that the elements' sizes are, in general, of the order of the cylinders radii and, given the size of the wavelength, each element is multi-wavelength sized.

Elastic wave modelling

Now, we consider the use of the PUFEM to model elastic wave problems, such as scattering of elastic waves by a rigid body. We choose the incident displacement field $\mathbf{u}^{in}$ as a superposition of pressure (P) and shear (S) plane waves travelling from the left to the right in the horizontal direction, which hits a circular rigid body in a linear homogenous and isotropic medium Ω. The incident field is given by

$$\mathbf{u}_{in} = \mathrm{i}k_P \exp(\mathrm{i}k_P x_1)\mathbf{e}_1 - \mathrm{i}k_S \exp(\mathrm{i}k_S x_1)\mathbf{e}_2, \tag{7}$$

where k_P and k_S are the pressure and shear wave numbers, respectively, and x_1 and x_2 are the coordinates of a point in the cartesian system $(\mathbf{e}_1, \mathbf{e}_2)$. The total displacement $\mathbf{u} = \mathbf{u}_{sc} + \mathbf{u}_{in}$, where $\mathbf{u}_{sc}$ denotes the scattered wave, satisfies the following elastic time harmonic equation

$$-\rho\omega^2\mathbf{u} - \nabla \cdot \boldsymbol{\sigma}(\mathbf{u}) = \rho\mathbf{f}, \tag{8}$$

where the stress tensor $\boldsymbol{\sigma}$ is defined, via the classical Hooke's law, by

$$\boldsymbol{\sigma}(\mathbf{u}) = \lambda\nabla \cdot \mathbf{u}\,\mathbf{I} + \mu(\nabla\mathbf{u} + \nabla\mathbf{u}^{\top}), \tag{9}$$

for a given displacement field $\mathbf{u} = u_1\mathbf{e}_1 + u_2\mathbf{e}_2$ where $(\mathbf{e}_1, \mathbf{e}_2)$ is a cartesian vector system, $\mathbf{I}$ is the identity matrix in

$\mathbb{C}^d \times \mathbb{C}^d$, λ and μ are the Lamé parameters of the elastic material, assumed constant, ρ is the density of the medium assumed constant as well, ω is the circular frequency and $\mathbf{f}$ is a body force. We will denote, respectively, by $\mathbf{n}$ and $\mathbf{t}$ the outward unit normal and tangent vectors to the boundary $\Gamma = \partial\Omega$ of the domain Ω. We impose the following Robin type boundary condition:

$$\boldsymbol{\sigma}(\mathbf{u})\mathbf{n} = \mathrm{i}\left((\lambda + 2\mu)k_P(\mathbf{u}\cdot\mathbf{n})\mathbf{n} + \mu k_S(\mathbf{u}\cdot\mathbf{t})\mathbf{t}\right) + \mathbf{g} \quad \text{on} \quad \Gamma, \tag{10}$$

where k_P is the pressure wave number and $\mathbf{g}$ is a source term. Here again, the source term $\mathbf{g}$ is introduced in expression (10) to avoid numerical errors due to the approximation of the artificial boundary condition as we are only interested in the validation of our numerical method.

Multiplying (8) by the complex conjugate of a test function $\bar{\mathbf{v}}$ and integrating by parts over Ω we get, taking into account (10), the following weak form

$$\begin{aligned}
&-\omega^2\rho \int_\Omega \mathbf{u}\cdot\bar{\mathbf{v}}\, d\Omega + \int_\Omega \boldsymbol{\sigma}(\mathbf{u})\cdot\nabla\bar{\mathbf{v}}\, d\Omega \\
&-\mathrm{i}\int_\Gamma \left((\lambda+2\mu)k_P\,(\mathbf{u}\cdot\mathbf{n})\,(\bar{\mathbf{v}}\cdot\mathbf{n}) + \mu k_S(\mathbf{u}\cdot\mathbf{t})\,(\bar{\mathbf{v}}\cdot\mathbf{t})\right)\, d\Gamma \\
&= \int_\Gamma \mathbf{g}\cdot\bar{\mathbf{v}}\, d\Gamma + \rho\int_\Omega \mathbf{f}\cdot\bar{\mathbf{v}}\, d\Omega.
\end{aligned} \tag{11}$$

We denote by $\{N_z\}$ the partition of unity by polynomial finite element shape functions, and respectively by m_P and m_S the numbers of approximating P and S plane waves. The displacement $\mathbf{u}$ is approximated as follows

$$\mathbf{u}_h = \sum_{z=1,n} N_z \left(\sum_{l=1,m_P} A^P_{z,l}\exp(\mathrm{i}k_P\mathbf{x}\cdot\mathbf{d}^l_P)\mathbf{d}^l_P + \sum_{l=1,m_S} A^S_{z,l}\exp(\mathrm{i}k_S\mathbf{x}\cdot\mathbf{d}^l_S)\mathbf{d}^l_{S,\perp} \right), \tag{12}$$

where h denotes the computational mesh size. The directions $\mathbf{d}^l_P$ and $\mathbf{d}^l_S$ are taken here uniformly distributed on the unit circle such that

$$\begin{aligned}
\mathbf{d}^l_P &= \left(\cos\left(\theta^l_P\right),\ \sin\left(\theta^l_P\right)\right)^\top,\ \theta^l_P = \frac{2\pi l}{m_P}, \\
\mathbf{d}^l_S &= \left(\cos\left(\theta^l_S\right),\ \sin\left(\theta^l_S\right)\right)^\top,\ \theta^l_S = \frac{2\pi l}{m_S}.
\end{aligned} \tag{13}$$

The orthogonal of vector $\mathbf{d}$ denoted by $\mathbf{d}_\perp$ is defined by $\mathbf{d}_\perp = (-d_2, d_1)$. The approximation (12) shows that the unknowns are no longer the nodal values of the displacement $\mathbf{u}_h$ but are now the amplitudes $A^P_{z,l}$ and $A^S_{z,l}$ attached to a given node z and corresponding to P and S plane waves travelling in the directions $\mathbf{d}^l_P$ and $\mathbf{d}^l_S$, respectively.

We are now in a position to derive a (conjugated) PUFEM approximation for (11), which leads to an invertible linear algebraic system, similar to (6), provided that the chosen approximating plane waves are linearly independent. For more details on the matrix implementation of (11) and its numerical solution, we refer the reader to reference [11].

In order to show that the current plane wave basis finite elements lead to drastic reduction of the computational effort, the total number of degrees of freedom ($totdof$) and the total number of storage locations ($totsys$) of the linear system matrix are compared when both the PUFEM and the polynomial based finite elements are used to solve the scattering problem described above. For the PUFEM model, the mesh of Figure 2 is considered with the plane wave basis (m_P, m_S) mentioned in Table 2, for increasing ω = 10, 20, 30 and 40. For the Finite Element Method (FEM), a uniform computational mesh is established with 9-noded finite elements and by taking around ten nodal points per S-wavelength. The extent of the computational domain around the circular body of radius a is $a \le r \le R$, such that $R = 2a$. All parameters a, λ, μ and ρ are taken equal to 1 with their respective corresponding units. The geometry of the finite elements is interpolated via Lagrange polynomials.

An example of contour plot of $|Re(\mathbf{u}_h)|$ is shown in Figure 2 when a horizontal P and S plane waves are simultaneously scattered by the rigid body. The considered circular frequency and the numbers of approximating plane waves are ω = 10 and $(m_P, m_S) = (16, 16)$, respectively. The L^2 error, ϵ_2 = 0.02%, shows again very good quality results. Note that the displacement associated to the P-wave scattering presents a symmetry with respect to the x_1 axis. However, the displacement analytical solution associated to the S-wave scattering is antisymmetric with respect to the x_1 axis. Consequently, the solution of the P and S waves simultaneous scattering is neither symmetric nor antisymmetric.

Table 2 shows the L^2 error, the total number $totdof$ of degrees of freedom and the total number $totsys$ of storage locations of the global matrices associated with PUFEM and FEM, for different values of the circular frequency ω. The results prove that PUFEM leads to better accuracy than FEM, with a significant reduction of both the total number of degrees of freedom and the total number of storage locations. For example, for ω = 10, the total number of degrees of freedom and the total number of storage locations are comparable but the PUFEM gives an L^2 error with two orders of magnitude smaller. For ω =20, 30 and 40, the PUFEM leads to lower L^2 errors and drastic reductions in the total number of degrees of freedom and the total number of storage locations; more than 90% and 75%, respectively, at ω = 40.

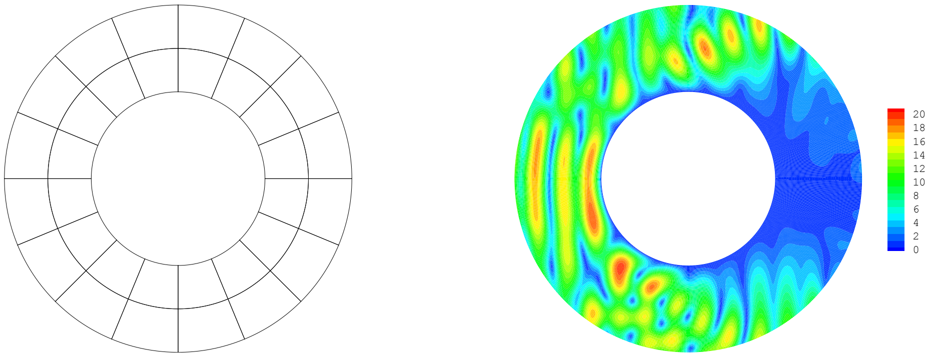

Figure 2: Simultaneous scattering of P and S waves by a rigid circular body, (left) considered mesh grid, (right) contour plot of $|Re(\mathbf{u}_h)|$ for $\omega = 10$, $\epsilon_2 = 0.02\%$.

ω	PUFEM				FEM		
	(m_P, m_S)	$totdof$	$totsys$	$\epsilon_2[\%]$	$totdof$	$totsys$	$\epsilon_2[\%]$
10	$(8, 8)$	$2,560$	$736,512$	0.03	$6,800$	$829,352$	1.22
20	$(16, 16)$	$5,120$	$2,943,488$	0.09	$26,400$	$6,179,952$	2.12
30	$(20, 20)$	$6,400$	$4,598,400$	0.70	$58,800$	$20,352,568$	3.09
40	$(32, 32)$	$10,240$	$11,758,832$	1.09	$104,000$	$47,648,000$	4.08

Table 2: Elastic wave scattering problem: comparison between PUFEM and FEM.

In the case of FEM, the computational time required for the evaluation of element matrices and the assembling process to form the final linear system represents a fraction of the time required during the solution process. However, for the PUFEM at the current stage, the computational burden shifts from the solution process to the evaluation of the element matrices where the integration of the highly oscillatory functions requires large numbers of points. Also, for large numbers (m_P, m_S) of approximating plane waves, the matrix of the linear system has a tendency to become ill-conditioned. It was shown in the past, that poor conditioning is an inherent feature on the plane wave decomposition technique. Therefore, efforts must be focused on either determining safe regions in terms of the influencing parameters over which the condition number stays within acceptable limits, or investigate the possibility of efficient preconditioning and solution procedures. Nevertheless, the PUFEM leads to a better level of accuracy with significant reduction in the total number of degrees of freedom and the total number of storage locations compared to FEM.

Conclusions

PUFEM numerical schemes are developed for the solution of the Helmholtz problems and the time harmonic elastic wave equations. They are validated on numerical examples dealing with wave scattering by circular rigid bodies. The proposed approach can incorporate many wavelengths per nodal spacing and hence allows us to keep the mesh of the computational domain unchanged for increasing frequency. It also leads to significant reductions of the total number of degrees of freedom and the total number of storage locations, and gives a better level of accuracy, compared to the polynomial based FEM. To make the proposed numerical scheme highly competitive more work is being done including the development of fast integration procedures, the investigation of preconditioning of the global linear system and the use of iterative solvers.

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A report on the Unwin lecture 2008:

"Designing for earthquake effects in Great Britain

The role that research has played in supporting UK earthquake engineers"

Edmund Booth
Consulting Engineer

Introduction

The Unwin lecture series was established by the Institution of Civil Engineers (ICE) in 1948, to be given on a subject related to engineering research. It commemorates William Unwin (1838 -1934), a prominent engineer of the Victorian and Edwardian eras, and is given every two years or so. I was asked to talk about the research I had carried out with Roger Musson, Bryan Skipp and others, which was triggered by the need to prepare National Annexes for Eurocode 8: Design of structures for earthquake resistance.

The lecture gave me an opportunity not only to report on this research (which was partly funded by the ICE's Research Fund) but also to reflect more generally on issues related to earthquake engineering research. A formal copy of the paper will be submitted in due course to the Institution for publication, but this is a summary of some of the ideas the lecture contained. You can see the lecture slides and hear the accompanying narrative by visiting the Institution's Online Lectures Portal accessed from the Institution's website (www.ice.org.uk); select Knowledge – Online lectures – Recorded events (page 2).

Seismic engineering in the UK

The earthquake engineering community forms one of the closest knit special interest groups in the UK, with particularly close and effective links between academics and design professionals. For one of the least seismically active countries in the world, that may be surprising, but it has a long tradition. The founding fathers of earthquake engineering, Robert Mallet and John Milne, were both British, while in the second half of the twentieth century, Nick Ambraseys continued the Mallet-Milne tradition by founding a school of engineering seismology at Imperial College, which gained an international reputation and importance. This continues today under Julian Bommer and Ahmed Elghazouli. There's a link with William Unwin here – he was the first professor of Civil and Mechanical Engineering at the Central Technical College, which later became Imperial College.

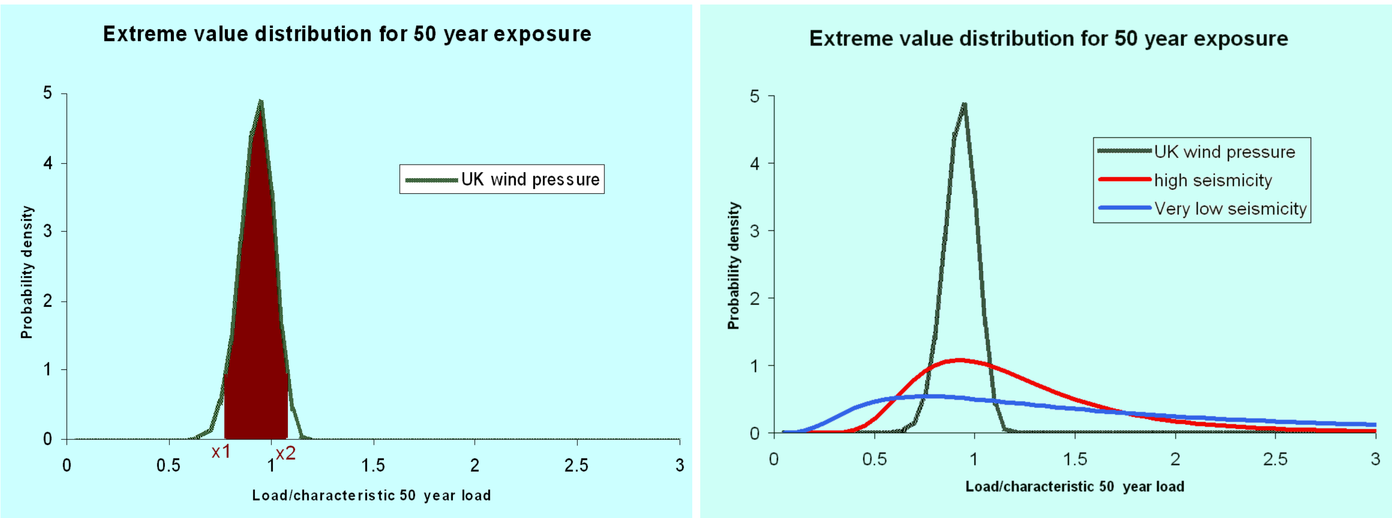
Then, in the late seventies, there was another hugely significant event for the development of British earthquake engineering. A group of enthusiasts got together to found SECED. Still going very strongly, SECED provides a forum for genuinely close and fruitful contacts between practitioners and academics which has proved enormously beneficial for both groups. The monthly meetings that the society holds keep us up to date with what's new and who the latest movers and shakers are, and the meetings give an opportunity for friendly and often stimulating debate. Equally important, networking goes on in the bar afterwards and that has a vital function too. Why has SECED, with its clumsy title and ungainly logo, proved to be so fertile, in territory that is seismically so quiet? Three reasons, I would suggest. Firstly, there was the growing need to provide seismic safety cases for the UK nuclear industry, and SECED was started at a time (it seems long ago) when nuclear power was attracting some of the best engineering talent. Secondly, the UK consulting industry has always worked in seismically highly active parts of the world, and as SECED was starting, there was an explosion both in the capability for dynamic analysis and an understanding of the true nature of seismic design issues. But there's a third reason for earthquake engineering's appeal in the UK that Roy Severn was fond of pointing out. Roy, a past president of the ICE who did much to further British interests in earthquake research, cited the intellectual challenge of the discipline, its intrinsic glamour, its international status and the pressing need to solve practical engineering problems (on tectonic plate boundaries if not the UK); together, these aspects proved an irresistible attraction to ambitious civil engineering departments like the one he ran at Bristol. Roy, incidentally, also proposed the ICE's Research Fund. It's not just Imperial College and Bristol that get involved; a survey in 2001 (ref 1) found that 13 university departments were conducting at least some research in seismic engineering.

For an earthquake engineer like myself working on a range of projects in the UK and overseas, this gives an excellent base to work from. There is much support for design in highly seismic areas where earthquakes provide a constant and immediate threat, and I have to admit that these are the challenges I enjoy most. But there is also an excellent research network to support and inform the decisions needed in the seismic design for UK structures.

Seismic hazard and risk in the UK

A glance at any seismic hazard map of Europe makes it clear that the United Kingdom is much less seismic than southern Europe. But can we say the hazard is negligible? Well, we do have earthquakes which cause some damage – for example Folkestone in 2007, and Market Rasen in 2008. The damage caused by Market Rasen and Folkestone is thought to have given rise to insurance claims of a few tens of millions of pounds, but there is no convincing evidence of any damage to engineered structures. The cost of those two earthquakes pales into complete insignificance in comparison with the cost, disruption and casualties – including deaths – caused by flooding in the UK these past few years. Since the Folkestone earthquake, the Association of British Insurers has put out 25 press releases relating to flooding but none at all on the events in Folkestone and Market Rasen. Severe wind storms and flooding in January and February 1990 alone cost over £3billion, and flooding in 2008 around a billion. The chimneys and loose masonry that were felled by recent British earthquakes would like as not have blown down in a gale sooner or later anyway. So why can't we forget about UK earthquakes and concentrate on more immediate problems?

The problem can be expressed mathematically in terms of probability distributions. Figure 1a shows probability distribution for the extreme value of wind pressures in



a) UK wind pressure probability distribution

b) Comparison between wind and seismic probability distributions

Figure 1: UK wind pressure distribution compared with earthquake acceleration distributions

the UK during a 50 year period. On this graph, the probability that the extreme value lies between two particular values – say x1 and x2 – is proportional to the area under the graph between those two values. It is clear that the fifty year extreme is very likely to occur within reasonably close bounds. Compare that with the earthquake situation (figure 1b). For a high seismicity area like San Francisco; you can see that there's much more variation in the likely extreme seismic acceleration than is the case for wind. For an area of very low seismicity, like Britain, the variation is greater still. There is a significant probability that the extreme during 50 years might be 2½ to 3 times the expected value, but a similar probability that it could be much less than half the mean. Should we design our structures for the low probability of a large earthquake, and could we justify this to the general public? The collective memory is just as likely to be from earthquakes at the other end of the distribution – in other words, that they seem to be completely negligible.

The reason for this great variability in earthquake extreme values is not hard to see. The UK is not expected to suffer great earthquakes but events up to Richter magnitude 6, even 6½, are possible. An earthquake of magnitude 5 to 6 can give rise to potentially very damaging ground motions in the epicentral area, but that area is quite small, far less than the area that was affected by a UK wind storm like that of 1987, which swept across most of southern Britain. Events of magnitude 5 to 6 are known to occur in the UK – there has been one in the last 100 years if you count the Dogger Bank earthquake of 1931, and there is good reason to believe that onshore events of this magnitude may have occurred in the last thousand years. But clearly, they are very rare, and since the area significantly affected is relatively small, the hazard at any one particular spot is very low. So the expected 50 year extreme at any location is low – and certainly negligible – but the maximum possible is potentially serious.

This was the nub of the dilemma that that faced us when drafting the UK National Annexes to Eurocode 8.

The application of Eurocode 8 in the UK

During 2005 to 2006, all six parts of EC8 were published by the BSI, together with a UK National Foreword which stated the following.

> *There are generally no requirements in the UK to consider seismic loading, and the whole of the UK may be considered an area of very low seismicity in which the provisions of EC8 need not apply. However, certain types of structure, by reason of their function, location or form, may warrant an explicit consideration of seismic actions. It is the intention in due course to publish separately background information on the circumstances in which this might apply in the UK.*

In order to help prepare this background information, two studies were carried out, which comprised the preparation of a UK seismic zoning map and a broad based review of the need for seismic design in the UK, and I will now briefly describe both of them.

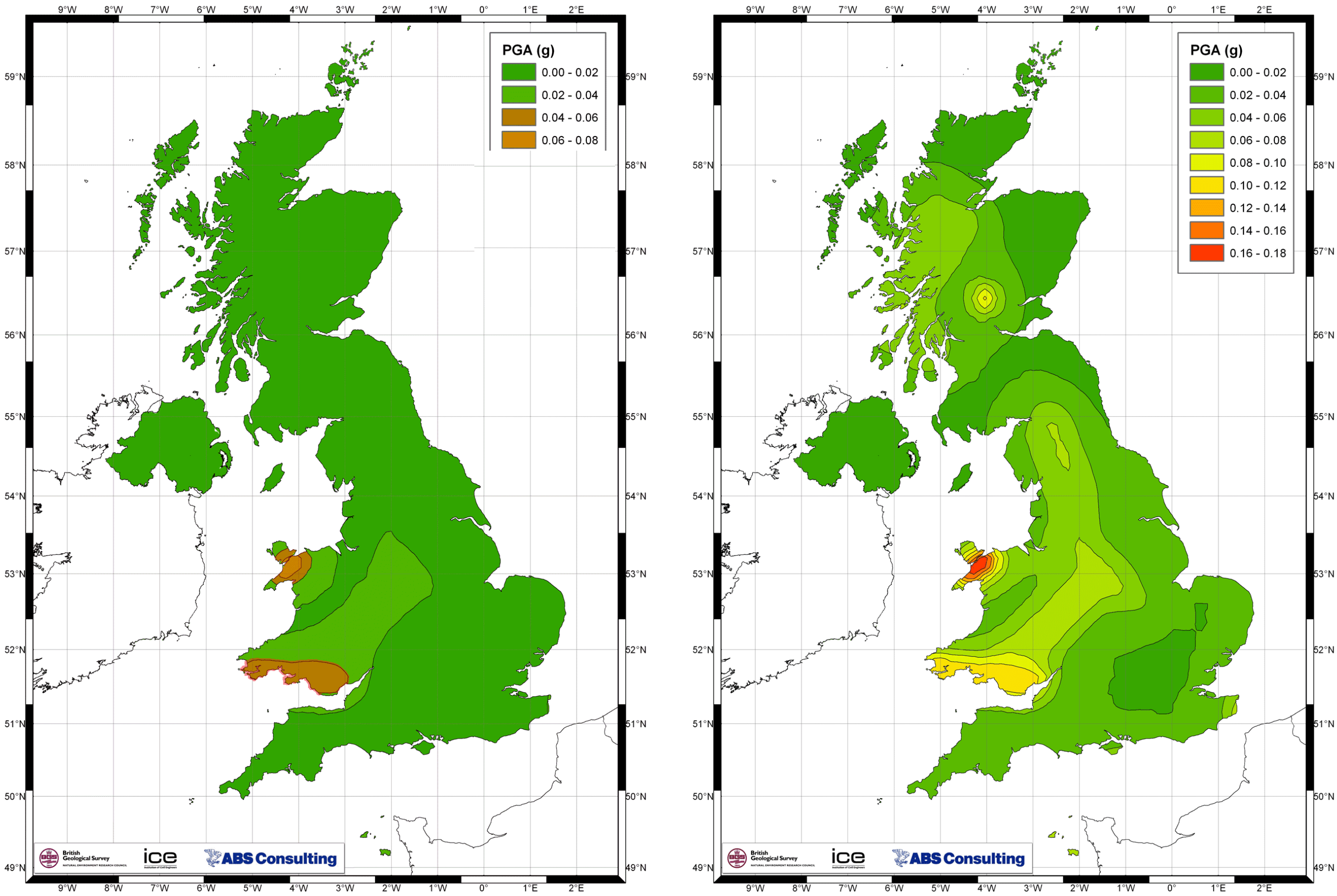
Study 1: The BGS seismic zoning study

Seismic hazard studies for the nuclear industry are specifically required to provide 'conservative' estimates of hazard. By contrast, Roger Musson and his colleagues at BGS Edinburgh set out to make the 'best estimate' of hazard; in other words, they used their best judgement rather than taking the worst credible option when there were decisions to make. Key to any seismic hazard assessment are the seismic source model (the geologically based assumptions about where earthquakes may arise) and the earthquake catalogue – a list of times, locations and magnitudes of past events. Due to budget limitations, BGS based these on ones previously developed at BGS, with only limited updating, but since these data had been developed at BGS over many years, this was not a major limitation. Another key decision to any hazard study is the choice of ground motion equations; these relate the ground motion at any given point to the location, size and type of earthquake that causes the motion. Musson elected to use two very recent equations, one from Imperial College, the other from California. At Julian Bommer's suggestion (actually over a pint of beer at a SECED meeting) an introductory meeting of UK seismologists was held, at which these and other procedures were agreed (and to some extent modified) before the main analysis work started.

The full BGS report (ref 2) is freely available from the SECED website. The mapping for 475 year return period which it contains is shown as Figure 2a. Only two small areas of Wales, coloured pink in the figure, exceeded the EC8 threshold for 'very low seismicity' of a peak acceleration of 4%g on rock. However, the 475 year return period is unlikely to capture the tail of the hazard distribution that proves so important in the UK. At the introductory meeting, it was agreed that Roger would also produce a map for a 2,500 year return period, and this is shown as the rather more interesting figure 2b.

Study 2: Establishing the need for seismic design in the UK

The second study, which I headed, was a general investiga-



a) 475 year return period **b) 2,500 year return period**

Figure 2: PGA hazard maps for the UK (from Musson & Sargeant, ref 2)

tion of the need to design for earthquake effects in the UK. In outline, the main conclusions were as follows. Firstly, we decided that the robustness provisions of present UK (non-seismic) standards provide sufficient seismic resistance for most structures. That conclusion was based on earlier studies of the robustness requirements for steel and concrete buildings, and also on a detailed review of current building regulations for domestic masonry. Another conclusion was that 475 years is too short a return period to define the design earthquake in an area of low seismicity, for the reasons discussed earlier. We recommended 2,500 years instead and that is something I for one would like to see incorporated in the next major revision of EC8. Based on a review of requirements in other low seismicity areas worldwide, we came up with a recommended procedure for establishing the need for seismic design in the UK. This is described in full in the report (ref 3), which is also freely available via the SECED website.

The advice in the UK National Annexes to EC8

Informed in part by the two studies just described, the UK National Annexes to EC8, which have now been published by the BSI, recommend that seismic design is not needed for Consequence Category 1 or 2 structures – those where failure would not result in major loss of human life, or major environmental or economic consequences. All normal commercial and residential buildings are thus excluded. CC3 structures are those where the consequences of failure would be large; some examples are a large grandstand, important hospitals, the Albert Hall or an LNG tank. Seismic design should at least be considered for all CC3 structures, but in many cases it may not be required, and I will touch on that in a moment. Where seismic design is recommended, the UK National Annex provides two options. The first is to use the standard spectral shape for Type 2 earthquakes in EC8 and anchor it the peak ground acceleration obtained from the BGS 2,500 year zoning map. Bearing in mind that EC8 recommends design for a 475 year period, that may seem very conservative. To some extent, that was intentional because of all the uncertainties, although the conservatism is somewhat reduced because no additional 'importance' factor is required, even for high consequence structures.

The other option is to work out the appropriate design spectrum from a site-specific study, without reference to the code shapes or the BGS map. That is a much more expensive option, because considerable amounts of specialist expertise are needed, but we anticipated that it would usually result in more favourable results. This site specific procedure is mandatory for high risk petrochemical plant, like LNG tanks, and it is also what has been done for many years in the nuclear industry, although design of nuclear plant is beyond the current scope of the Eurocodes.

The recommendation of the UK National Annex is then to carry out an analysis to EC8, using a low q or ductility factor. However, the special seismic detailing requirements of EC8, which constitute the bulk of the code's provisions may be neglected. Essentially, the requirement is limited to a strength check under a lateral force which may exceed that due to wind.

What advice is given on how to decide whether a high consequence category structure actually needs to be subjected to seismic analysis? In fact, the National Annexes give no advice, referring instead to a BSI background paper, PD 6698 (ref 4), which is due to be published during spring 2009. This in turn refers to the ICE study (ref 3), which does provide a procedure. The recommendations in the ICE study were intended to be pragmatic but they are far from self-evident; many other choices were possible. Also, it is important to note that they have no statutory force; they are just recommendations in an ICE report which engineers can use, modify or ignore as they please. My hope is that, with experience of use, they will in time graduate, almost certainly modified and refined, into PD 6698. At the moment, I have to say that I don't expect that designers of a hospital on poor ground in South Wales will necessarily be persuaded to make seismic checks on their building, or even that they will know that it is recommended. My guess is that there will be more immediate implications for high risk petrochemical plant like LNG tanks and high pressure pipelines, and my hope is that the UK National Annexes, together with the Background Document and the ICE report, will provide a logical framework in which to make rational decisions.

Implications for the nuclear field are more controversial. Nuclear power plants are specifically outside scope of EC8. That is because some crucial aspects of their performance requirements are not dealt with by the code. However, at the moment, much UK nuclear seismic work uses an awkward, and to my mind unsatisfactory mix of BS and US codes, although seismic nuclear safety cases are beginning to refer to clauses in Eurocode 8. The ICE funded work does not address many (or even most) of these issues, but it provides a few starting points and a confidence that there could be a way forward to develop a European seismic standard for nuclear power plants, based on EC8. Maybe we could do this in collaboration with our European colleagues, perhaps with some help from the ICE Research Fund.

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This is the first in a series of articles from the one day seminar *Seismic Analysis using Finite Elements* organised by SECED and NAFEMS and held in London, 5 December 2008. Andrew Coatsworth writes about quality assurance in numerical analysis.

Numerical structural analysis – quality and transparency

Andrew Coatsworth
HM Nuclear Installations Inspectorate

Summary

Other papers, together with the NAFEMS book on seismic analysis (Reference 1), deal with some of the technical aspects of carrying out seismic analysis using finite elements. This paper touches on the topics of quality and transparency, which pervade the whole process from the initial decision of the designer that a numerical analysis is required, through to the final reporting of the work and that vital stage of archiving the information.

Of the twin topics — Quality and Transparency — Quality ("getting it right") is the better documented, e.g. by the NAFEMS QS001 publication (Reference 2). Transparency ("showing what has been done") is less understood, both as a need and the means of its achievement. Quality and Transparency are not separate topics, and some of the issues in this paper belong under both headings.

Although most of my experience is from the nuclear industry, the following observations regarding numerical structural analysis are neither specific to the nuclear industry, nor indeed to seismic analysis. Indeed, an earlier oral presentation version of this paper was favourably received in the context of highways traffic forecasting!

Credibility and Reproducibility

For an alternative categorisation of the same problem I recommend a close reading of the Editorial Policy Statement on Numerical and Experimental Accuracy published by The American Institute of Aeronautics and Astronautics (AIAA). The AIAA has a firm editorial policy (Reference 3) aimed at to improving the credibility and reproducibility of the numerical aspects of the simulation results in papers that it accepts for publication. The AIAA states that:

> *The AIAA journals will not accept for publication any manuscript reporting (1) numerical solutions of an engineering problem that fails to adequately address the accuracy of the computed results or (2) experimental results unless the accuracy of the data is adequately presented.*

The AIAA states that authors should address the following:

- Statement of Numerical Methods;
- Minimum formal accuracy of Numerical Methods;
- Statement of Code Verification Activities;
- Spatial Convergence Accuracy;
- Temporal Convergence Accuracy;
- And, Iterative Convergence Accuracy.

Elaborations of these expectations are given by the AIAA in Reference 3. I see no reason why I as a nuclear safety regulator should have lesser acceptance criteria in respect of numerical structural analysis in support of a nuclear safety case than the AIAA has for technical publications.

The need for transparency

An analyst is unlikely to work in isolation, but needs to convey the particulars of the analysis to others such as:

- Originating organization, e.g. supervisor;
- Design team;
- Client;
- Reviewer (for research or technical publication).

There may be a need for sufficient information to be avail-

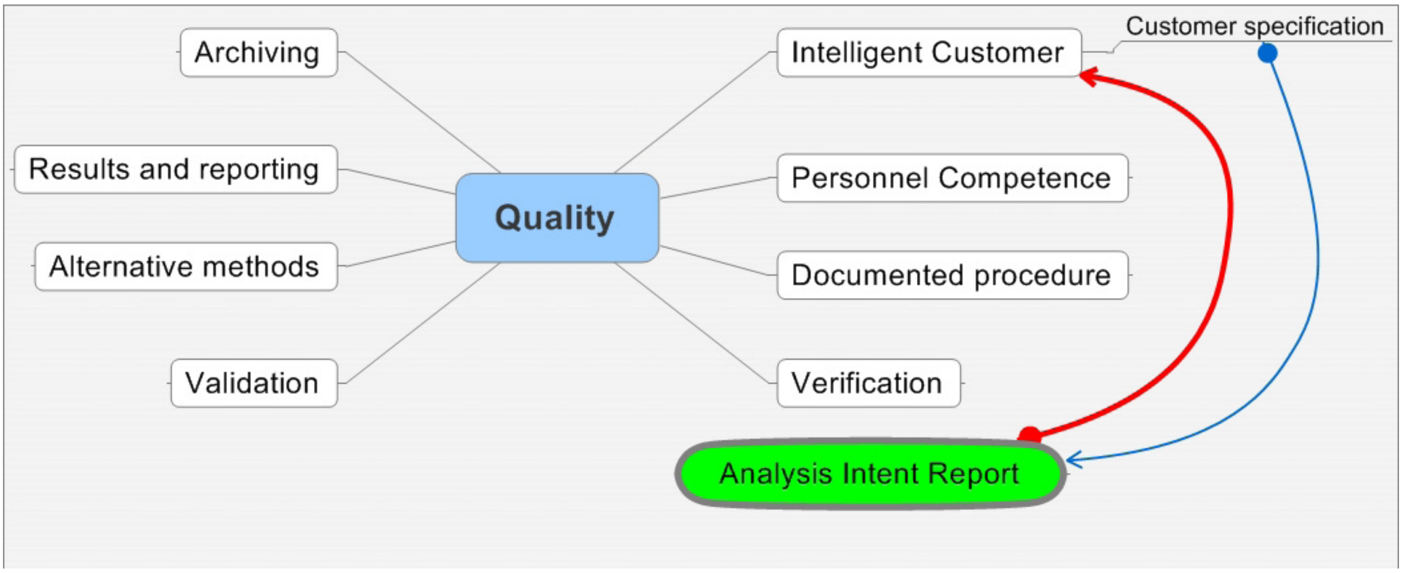

Figure 1. Quality plan

able for one to replicate or otherwise check the analysis.

Additionally in highly regulated industries, the regulator, although not normally performing check calculations, requires visibility as to what analysis has been done.

I believe that the only class of structure in the UK routinely required to have a totally independent structural calculation is that of Category 3 highway bridges and Category 3 railway bridges. For all other structures, including Category 2 highway and railway bridges, dams, tall buildings and even nuclear facilities, the originating organization, client and/or regulator may do one of the following:

- Nothing;
- Sanity test;
- Independent calculation of a sample;
- Or, full independent check using diverse software.

The analyst should provide the analysis and supporting information in such a way that a third party can sufficiently understand what the analysis was intended to achieve and how this was achieved. The Third Party may be:

- a supervisor;
- a designer;
- an Independent Technical Authority;
- a Panel Engineer (in the case of dams);
- or, a regulator.

I term the provision of analysis and other information in a form to aid such comprehension as *transparency*.

Transparency is not just for the short term, e.g. the design phase, but for the subsequent life of a structure, such that:

- the safety case may be maintained;
- modifications may be engineered;
- any failure may be investigated;
- and, if necessary that the original analysis may be recovered from the archive.

An early form of numerical structural analysis for static loading was the long obsolete method of moment distribution, in which fixed end moments in a framed structure were successively relaxed, each iteration being manually recorded, typically in a tabular form adjacent to a sketch of the structural idealisation. Moment distribution was very transparent. As software becomes ever more powerful, transparency tends to diminish. This is not to decry the very significant advantages of the great leaps in analysis capability, but to remind engineers of the greater effort required to achieve transparency compared to that for simpler techniques.

Quality

Remember the 5Ps: Proper Preparation Prevents Poor Performance. Write a Quality Plan (Figure 1). This may be very simple, being proportionate to the problem in hand. Annex A of Reference 2 makes a useful distinction between the importance of the engineering application, in our case the structure being analysed, and the simulation category of importance, which depends on both:

- The structure;
- And, the role of the analysis.

Consider the requirements of a Quality Management System:

- ISO 9001:2000 (Reference 4);
- Or, for the nuclear industry that of the IAEA (Reference 5).

NAFEMS QSS 001:2007 (Reference 2) is a supplement to a quality management standard, such as ISO 9001, and is intended for engineering simulation employing computational methods.

The analysis should commence with a specification as to what is required. There are two situations: one where a customer, internal or otherwise, specifies the analysis that is required, and one where the person carrying out the analysis self specifies the requirements.

One attribute of an Intelligent Customer (Reference 6) is "Knowing where and when to seek advice and on receipt of this advice understanding the implications." Thus an Intelligent Customer's role is to:

- Specify;
- Monitor;
- Accept.

An Intelligent Customer is able to specify the work so that the contractor:

- Clearly understands the requirements;
- And, is aware of the context of the work.

An Intelligent Customer should be able to:

- Understand the detail of the work undertaken;
- Challenge the methodology;
- Interpret the results.

After the specification comes the implementation, and this is strongly dependent on the person undertaking the structural analysis. For the analyst NAFEMS attempts (Reference 2) not entirely successfully to define Personnel Competence, which may be a regulatory or other requirement, e.g.:

- Railway and Other Guided Transport Systems Safety Regulations (2006);
- Nuclear Site Licence Condition 12;
- And/or a Commercial and Professional Indemnity requirement.

Procedures aid implementation of the analysis specification, and incidentally aid transparency. A documented procedure should be established, qualified, documented, implemented and maintained.

Beware of mission creep, which can lead a model being used for a purpose for which it was neither intended nor is suitable, for example, requests for floor response spectra from a model intended purely for structural engineering use.

With respect to the actual modelling, definitions of verification and of validation vary, in some cases being interchanged. For the purposes of this paper I am using:

- Verification:
  - ▹ Procured software fulfils functional specification;
  - ▹ Dynamic verification, also known as Test or Experimentation;
  - ▹ Static verification, also known as Analysis.

One must also must verify internally developed software.

- Validation:
  - ▹ Problem idealisation;
  - ▹ Numerical approximation;
  - ▹ Mesh;
  - ▹ Element type;
  - ▹ Convergence/stability.

In dynamic analyses there is an unfortunate tendency of many users of commercial software to rely excessively on the iteration interval (e.g. the maximum time step) calculated by the software. A failure to understand the limitations of the inbuilt algorithm may lead to a lack of convergence and/or stability, which is not always self-evident from the numerical results.

Although prominent in many quality systems, in my view, check lists have mixed benefits.

Alternative methods to validate a solution may include:

- Hand calculation;
- Approximation;
- Alternative software;
- Or, Benchmarking modelling results with actual behaviour.

It may seem obvious, but computational results and reporting should be such as to aid interpretation.

A final vital stage in the quality plan should include archiving of the source data.

Transparency

Transparency is showing what you intend to do and finally what you have done, while justifying any deviations.

It is good practice to specify in advance the structural analysis to be performed, as this:

- Aids bridging of the designer/analyst gap;
- Allows confirmation of the analysis intent with third parties before modelling effort is committed;
- In commercial work, reduces the scope for contractual disagreements.

The specification is sometimes known as an Analysis Intent Document. Some engineers advocate a combined Design/Analysis Intent Document, or Method Statement.

Models may have phases broadly corresponding to those of the engineering design:

- Concept model;
- Scheme model;

- Detailed model.

Often only the detailed model appears to be made available to regulators, such as myself, which can be frustrating if we believe a simple, concept model exists. Simple concept models often aid understanding, while detailed models may be essential for design. Unfortunately, such concept models are sometimes the electronic equivalent of the back of the envelope initial calculation:

- not quality assured;
- not updated as the design evolves;
- not made available to third parties as an aid to transparency;
- and discarded into the waste paper basket or its computer simile.

Transparency aids continuity between analysts, as these may change during the project life. Modelling can go wrong due for example to successive analysts applying nodal constraints in a different manner.

The geographical location of the model can become a problem if a lack of transparency requires a third party to actually sit down with an analyst at the computer screen in order to comprehend what has been done. With the globalisation of the engineering market this is becoming quite an issue.

Consider the form of the output from finite element structural analysis:

- Contour plots
  - ▹ Pictorial representation, especially of data from shell elements, aids comprehension of force/moment distribution and approximate location of peak values, but may not reveal peak values.
- Tabulated nodal data
  - ▹ Retains nodal peak values but does not aid understanding of force/moment distribution.
- Semi-processed output
  - ▹ Convenient for designer, but loss of information occurs. For example, there is a loss of sign in a seismic analysis following application of SRSS, and can lead to a black box mentality; it can be helpful to just look at the main modes individually if they contribute a reasonable proportion of the total response.

In interpreting the results be aware of the limitations of the model idealisation, including the consequences of:

- Centre-line modelling;
- And, local load eccentricity.

Conclusions

Quality and Transparency in numerical structural analysis are important, and to achieve these objectives, which may be more difficult than some of the technical problems, it is concluded that engineers should:

- Plan, e.g. in a Quality Plan;
- Say what is be done, eg in an Analysis Method Statement;
- Agree this in advance of modelling with the relevant parties as necessary;
- Carry out the intended analysis;
- Demonstrate compliance with the Method Statement, or justify any deviations;
- Show what has been done;
- And, maintain records.

Acknowledgement

I am thankful to Mr Andy Campbell and Mr John Maiden, both of Sellafield Sites Ltd, for technical discussions on the issue of transparency, and to Prof Norman Jones of Liverpool University, who drew to my attention the AIAA Editorial Policy on numerical and experimental accuracy.

These are the views of the author and do not necessarily represent the view of HSE.

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Notable Earthquakes July – September 2008

Reported by British Geological Survey

Issued by: Davie Galloway, British Geological Survey, January 2009.
Non British Earthquake Data supplied by The United States Geological Survey.

			Time			Dep	Magnitude			
Year	Day	Mon	UTC	Lat	Lon	km	M_L	M_b	M_W	Location
2008	01	JUL	00:17	10.37S	75.51W	33			5.5	CENTRAL PERU
At least 45 people injured, around 90 houses damaged or destroyed and several roads destroyed, by landslides, in Oxapampa and Huancabamba.										
2008	02	JUL	03:14	53.36N	0.41W	17	1.5			MARKET RASEN, LINCS
2008	02	JUL	10:37	52.10N	3.38W	11	2.1			BUILTH WELLS, POWYS
2008	02	JUL	19:05	58.12N	3.12W	7	1.9			MORAY FIRTH
2008	03	JUL	17:17	58.12N	3.09W	5	1.6			MORAY FIRTH
2008	03	JUL	17:50	58.12N	3.09W	5	1.5			MORAY FIRTH
2008	03	JUL	18:27	58.13N	3.11W	5	1.7			MORAY FIRTH
2008	03	JUL	21:40	59.90N	1.96E	10	2.4			NORTHERN NORTH SEA
2008	05	JUL	02:12	53.88N	152.89E	633			7.7	SEA OF OKHOTSK
2008	08	JUL	09:13	15.99S	71.75W	123			6.2	SOUTHERN PERU
One person killed and several buildings damaged in Arequipa.										
2008	15	JUL	03:26	35.80N	27.86E	52			6.4	GREECE
One person killed on Rhodes.										
2008	19	JUL	02:39	37.55N	142.21E	22			7.0	HONSHU, JAPAN
A small tsunami observed along the coast of Fukushima and Miyagi.										
2008	19	JUL	09:27	11.04S	164.49E	11			6.6	SANTA CRUZ ISLANDS
2008	22	JUL	16:03	53.40N	0.46W	21	1.9			MARKET RASEN, LINCS
2008	23	JUL	00:03	53.05N	4.15W	11	1.6			CAERNARVON
Felt in Penygroes, Bangor, Groeslon, Beddgelert, Llanberis and Dyffryr Ardudwy, Gwynedd (3 EMS).										
2008	23	JUL	15:26	39.80N	141.46E	108			6.8	HONSHU, JAPAN
One person killed, at least 200 injured and over 90 buildings damaged in northern Honshu.										
2008	23	JUL	19:54	32.75N	105.50E	10			5.5	EAST SICHUAN, CHINA
2008	24	JUL	07:09	32.75N	105.54E	10			5.7	EAST SICHUAN, CHINA
One person killed, 17 injured and over 1,000 houses destroyed in Sichuan.										
2008	26	JUL	18:51	24.79N	90.54E	18		4.8		BANGLADESH
At least 25 people injured in Dhaka.										
2008	29	JUL	18:42	33.95N	117.76W	15			5.4	CALIFORNIA
Eight people injured and minor damage reported in the Brea and Wilshire Districts of Los Angeles.										
2008	01	AUG	08:32	32.04N	104.72E	7			5.7	EAST SICHUAN, CHINA
At least 231 people injured and 3,000 houses damaged in Beichuan and Pingwu.										
2008	04	AUG	02:52	56.46N	5.30W	7	1.8			LOCH ETIVE, ARGYLL
2008	05	AUG	09:49	32.76N	105.49E	6			6.0	EAST SICHUAN, CHINA
Four people killed, 29 injured and several buildings damaged in Qingchuan area.										
2008	07	AUG	12:13	57.52N	5.69W	7	1.6			SHEILDAIG, HIGHLAND
2008	08	AUG	22:01	51.95N	1.68E	9	2.2			HARWICH, ESSEX
Offshore location, 25km east of Harwich.										

Notable Earthquakes (continued)

<table>
<tr><th>Year</th><th>Day</th><th>Mon</th><th>Time UTC</th><th>Lat</th><th>Lon</th><th>Dep km</th><th>Magnitude M_L</th><th>M_b</th><th>M_W</th><th>Location</th></tr>
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<tr><td>2008</td><td>09</td><td>AUG</td><td>09:56</td><td>52.34N</td><td>2.51W</td><td>11</td><td>1.9</td><td></td><td></td><td>LUDLOW, SHROPSHIRE</td></tr>
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<tr><td>2008</td><td>12</td><td>AUG</td><td>22:22</td><td>53.38N</td><td>2.57W</td><td>9</td><td>1.5</td><td></td><td></td><td>WARRINGTON, CHESHIRE</td></tr>
<tr><td colspan="11">Felt in Warrington (2-3 EMS).</td></tr>
<tr><td>2008</td><td>21</td><td>AUG</td><td>04:38</td><td>53.32N</td><td>0.63W</td><td>15</td><td>1.5</td><td></td><td></td><td>LINCOLN, LINCONSHIRE</td></tr>
<tr><td>2008</td><td>21</td><td>AUG</td><td>12:24</td><td>25.04N</td><td>97.68E</td><td>10</td><td></td><td></td><td>6.0</td><td>MYANMAR</td></tr>
<tr><td colspan="11">Five people killed, 127 others injured and severe damage in Yingjiang, China.</td></tr>
<tr><td>2008</td><td>23</td><td>AUG</td><td>08:57</td><td>48.42N</td><td>3.74W</td><td>15</td><td>2.6</td><td></td><td></td><td>NORTHWEST FRANCE</td></tr>
<tr><td>2008</td><td>23</td><td>AUG</td><td>12:52</td><td>59.99N</td><td>4.88E</td><td>10</td><td>2.8</td><td></td><td></td><td>SOUTHERN NORWAY</td></tr>
<tr><td>2008</td><td>25</td><td>AUG</td><td>13:21</td><td>30.90N</td><td>83.52E</td><td>12</td><td></td><td></td><td>6.7</td><td>WESTERN XIXANG</td></tr>
<tr><td colspan="11">Severe damage occurred in Zhongba County.</td></tr>
<tr><td>2008</td><td>27</td><td>AUG</td><td>23:54</td><td>49.07N</td><td>4.19W</td><td>15</td><td>1.7</td><td></td><td></td><td>NORTHWEST FRANCE</td></tr>
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<tr><td colspan="11">Over 30 people killed and more than 580 injured in Huili, Chuxiong, Panzhihua and Kunming. Thousands of buildings, including many schools, damaged or destroyed and several bridges, roads and reservoirs also suffered damage in the region.</td></tr>
<tr><td>2008</td><td>30</td><td>AUG</td><td>19:33</td><td>53.65N</td><td>3.16W</td><td>6</td><td>1.6</td><td></td><td></td><td>IRISH SEA</td></tr>
<tr><td>2008</td><td>31</td><td>AUG</td><td>08:31</td><td>26.23N</td><td>101.97E</td><td>10</td><td></td><td></td><td>5.5</td><td>SICHUAN/YUNNAN, CHINA</td></tr>
<tr><td colspan="11">Two people killed in Panzhihua.</td></tr>
<tr><td>2008</td><td>08</td><td>SEP</td><td>18:52</td><td>13.50S</td><td>166.97E</td><td>110</td><td></td><td></td><td>6.9</td><td>VANUATU</td></tr>
<tr><td>2008</td><td>09</td><td>SEP</td><td>03:07</td><td>3.94N</td><td>103.06E</td><td>25</td><td></td><td>5.4</td><td></td><td>SUMATRA, INDONESIA</td></tr>
<tr><td colspan="11">Two people killed and 113 homes damaged in Lahat.</td></tr>
<tr><td>2008</td><td>10</td><td>SEP</td><td>11:00</td><td>26.74N</td><td>55.83E</td><td>12</td><td></td><td></td><td>6.1</td><td>SOUTHERN IRAN</td></tr>
<tr><td colspan="11">Seven people killed and at least 30 injured in the Bandar Abbas area.</td></tr>
<tr><td>2008</td><td>10</td><td>SEP</td><td>13:08</td><td>8.09N</td><td>38.72W</td><td>10</td><td></td><td></td><td>6.6</td><td>MID-ATLANTIC RIDGE</td></tr>
<tr><td>2008</td><td>10</td><td>SEP</td><td>15:05</td><td>51.85N</td><td>3.41W</td><td>14</td><td>1.5</td><td></td><td></td><td>BRECON, POWYS</td></tr>
<tr><td>2008</td><td>11</td><td>SEP</td><td>00:00</td><td>1.89N</td><td>127.36E</td><td>96</td><td></td><td></td><td>6.6</td><td>HALMAHERA,INDONESIA</td></tr>
<tr><td>2008</td><td>11</td><td>SEP</td><td>00:20</td><td>41.89N</td><td>143.75E</td><td>25</td><td></td><td></td><td>6.8</td><td>HOKKAIDO, JAPAN</td></tr>
<tr><td>2008</td><td>16</td><td>SEP</td><td>21:47</td><td>17.44N</td><td>73.92E</td><td>10</td><td></td><td>5.0</td><td></td><td>MAHARASHTRA, INDIA</td></tr>
<tr><td colspan="11">One person killed, 20 injured and over 1,500 buildings damaged in the Daund area.</td></tr>
<tr><td>2008</td><td>18</td><td>SEP</td><td>21:01</td><td>51.04N</td><td>2.87W</td><td>8</td><td>1.2</td><td></td><td></td><td>BRIDGWATER, SOMERSET</td></tr>
<tr><td>2008</td><td>19</td><td>SEP</td><td>05:23</td><td>49.16N</td><td>3.88W</td><td>5</td><td>1.7</td><td></td><td></td><td>NORTHWEST FRANCE</td></tr>
<tr><td>2008</td><td>21</td><td>SEP</td><td>08:31</td><td>49.49N</td><td>0.02W</td><td>5</td><td>2.4</td><td></td><td></td><td>NORTHERN FRANCE</td></tr>
<tr><td>2008</td><td>29</td><td>SEP</td><td>15:19</td><td>29.76S</td><td>177.68W</td><td>36</td><td></td><td></td><td>7.0</td><td>KERMADEC ISLANDS</td></tr>
<tr><td>2008</td><td>30</td><td>SEP</td><td>20:46</td><td>58.08N</td><td>3.19W</td><td>9</td><td>2.4</td><td></td><td></td><td>MORAY FIRTH</td></tr>
</table>

This is the second in a series of articles from the one day seminar *Seismic Analysis using Finite Elements* organised by SECED and NAFEMS and held in London, 5 December 2008.
Rob Smith provides an insight into the engineering challenges posed by tall buildings.

Seismic design and analysis of tall buildings

Rob Smith
Associate Director, Advanced Technology and Research, Arup, London

Summary

There is a resurgence in the construction of tall buildings at the beginning of the 21st century, the driving forces for this being both economic prosperity and global urbanisation. Many of the current seismic design codes used for these designs are based upon design and analysis techniques dating back 40 years.

A new generation of guidelines and analysis techniques is being developed for reflect the behaviour of tall buildings and the latest computing tools available. This presentation focuses on examples of how this is done and how the methods differ from regular seismic analysis.

Introduction

The majority of existing seismic design codes make little provision for the design of tall buildings. The International Building Code and its forerunner UBC have origins dating back several decades when tall buildings (in seismically active regions) were rarely above 15 storeys. Indeed, the maximum height specified in the height limitation table is 240ft for zone 4. Eurocode 8 has more modern origins but has its focus on low to medium rise buildings.

Tall buildings differ from low to medium-rise buildings in the following key areas:

- Higher modes of vibration will often dominate the response, unlike low-rise buildings where the primary mode is dominant.
- The structural framing used for high-rise is often different in nature to low-rise. For instance moment frame structures are suitable for low-rise but not for high-rise. Outrigger structures are not used in low-rise construction and not considered in seismic design codes.
- The use of a single strength modification factor (*R* or *q*) is not appropriate in tall building design, where the distribution of ductility and its effect on building response may not be even.
- Owing to the uneven distribution of ductility, linear analysis techniques are not suitable.
- Similarly, non-linear static analysis (pushover analysis) is not suitable, owing to the dominance of higher modes.
- Prescriptive rules about, for instance, interstorey drifts are not appropriate for tall buildings with different deflected shapes.

The deficiencies in linear analysis and prescriptive rules have been recognised in China and Japan for many years. In Japan, a performance based design philosophy has been compulsory in all buildings over 60m, since 1981. Similarly in China, PBD is required for buildings outside of prescribed limits and the design must be reviewed by a panel of experts.

In the west, and in places where codes are derived from US and European standards, the recognition of the deficiencies in codes has been building over a number of years. More recently, formal guidelines on the analysis and design of tall buildings has been published.

Suitable guidance on non-linear analysis can be found in FEMA 356. (FEMA 356 has been republished as ASCE 41.) Guidelines for performance based seismic design of high rise buildings have been published by regulatory bodies in Los Angeles (LATBSDC, 2008) and San Francisco (SEAONC, 2007). Finally, there is “Recommendations for Seismic Design of High Rise Buildings” (CTBUH, 2008)

Suitable modelling and analysis techniques

The most versatile method of structural seismic analysis of tall buildings is non-linear response history analysis and this is recognised in the guidelines previously referenced. The key steps of such an analysis are as follows:

- A linear structural analysis model should be built and used to examine static and dynamic behaviour.
- The model should include secondary elements where these are likely to have an influence on global or local behaviour. For instance, the coupling effect of flat slabs should be included unless negligible.

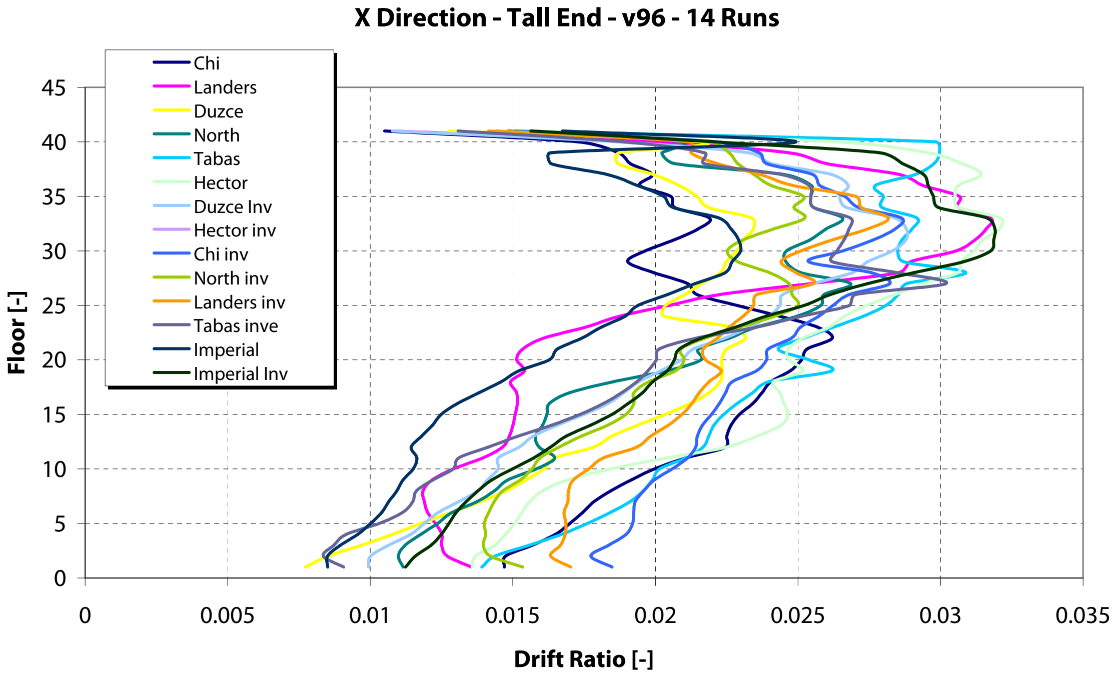

Figure 1. Variation of interstorey drift for different ground motions

- The areas where yielding is likely to occur should be identified. Typically this would be the base of walls and column, beams, braces etc.
- The building should be designed for strength using either the factored wind load or frequent earthquake, combined with dead and live.
- The strength of lateral load resisting structure should be assessed. The strength should be based upon "Best Estimate" properties, rather than "Design" properties, which include a margin of safety.
- This strength should be applied to the non-linear model.
- Ground motions should be generated that are appropriate to the design earthquake and location of the building. These motion histories can either be spectrally matched or scaled. For further discussion of these methods see the CTBUH document.
- The ground motions should be applied as "enforced accelerations." Between 3 and 7 sets of motions are required.
- For each analysis, the following checks should be made:
  - ▹ Plastic hinge rotations for ductile actions should remain within recommended limits.
  - ▹ For brittle actions (shear and compression), the measured forces should be within design limits. This may require increases in design capacity.
  - ▹ Interstorey drifts can be looked at to give an indication of deflection and damage to the building

Further details of the analysis requirements are given in the CTBUH document and FEMA 356.

Typical results

Results can either be viewed graphically or as a summary text file. Either way, a significant degree of post processing of data is required to give confidence in the results. This is because there is significant variation in the response of a non-linear model. This can be seen graphically in Figure 1, where the interstorey drift is plotted for different ground motions. Each motion was spectrally matched so all had the same response spectrum curve.

References

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Secretary General

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- Global Earthquake Model (GEM) is a five-year, €35M public-private initiative with the goal of establishing global independent standards for calculating and communicating earthquake risk worldwide (www.globalquakemodel.org). With over half its funding secured, GEM will launch formally in February 2009 and seeks a senior leader for its executive team.
- **Position Description**
  The Secretary General is the senior executive of GEM and the leader of the management team. Responsibilities include strategic direction in cooperation with the Science Board, oversight for execution of technical and scientific activities, ongoing fundraising, and organizational fiscal accountability. The Secretary General reports to the GEM Governing Board, which consists of representatives from each public and private sponsor.
- **Selection Criteria**
  The successful candidate will have a proven record of executive ability at a senior level in a technically-driven organization. The candidate must have the ability to think and act strategically to cultivate a broad foundation of external support, whilst empowering and building trust internally among a diverse scientific team. International travel is required. English language skills for business communications and negotiation must be impeccable, and fluency in additional languages is preferred.
- **Location** Pavia, Italy (part or preferably full-time).
- **Target Start Date** mid April, 2009.

Submit letter of interest, qualifications, business writing sample, and 5 references by **15th March 2009** to: Saverio Bisoni, European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Via Ferrata, 1 - 27100 Pavia, Italy.