

# NEWSLETTER

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# Rocking of Structures During Earthquakes: From Collapse of Masonry to Modern Design

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At the 27th February 2013 evening meeting, Dr Matthew DeJong (University of Cambridge, Engineering Department) gave a presentation on rocking during earthquakes, drawing parallels between the collapse of masonry structures and the design of modern structures. The presentation primarily focused on pulse-type ground motions (such as those often measured near

faults), and included discussion of scale effects, flexibility effects, and the need for better assessment and design methods. This paper will summarise certain aspects of the presentation, and then provide a brief comparison of code-based methods for rocking assessment in response to post-presentation discussion.

## 1. Presentation Summary

### Collapse of masonry

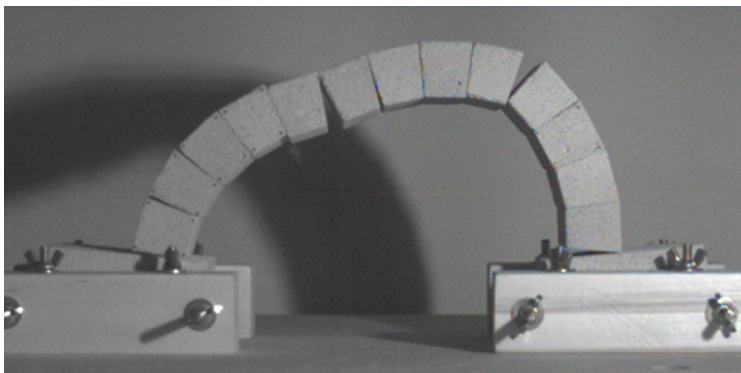
The potential collapse of masonry structures during earthquakes was introduced by consideration of the seismic response of a dry-stone masonry arch subjected to horizontal ground motion. Small scale experimental tests demonstrate that horizontal ground acceleration causes rocking motion (Figure 1a). To model arch rocking analytically, a reflecting four-hinge single-degree-of-freedom (SDOF) mechanism was presented. While a SDOF mechanism is clearly a simplification of actual behaviour, the analytical model provides a method to model the complicated dynamic response in a feasible manner. Comparison between analytical modelling and experimental tests demonstrated reasonably good agreement for prediction of collapse (DeJong et al., 2008).

The second type of masonry structure considered was the stone spire. Spires, being slender, are vulnerable to earthquake damage, and several examples of collapse or damage were given. The stone spire of Christchurch Cathedral collapsed in 1888 (Figure 1b) and 1901. The spire was rebuilt in lead-clad timber after the 1901 collapse, and it is this timber spire that collapsed in the 2011 Christchurch Earthquake. The collapse of the spire of Colchester in the Great English Earthquake of 1884 was also discussed, including a first-hand account which describes rocking collapse. The severe damage to the spire of the church of St Mary Magdelene in Waltham on the Wolds in the 2008 Lincolnshire Earthquake was then used to discuss the collapse of spires more generally.

Results from analytical modelling, Discrete Element Modelling, and experimental testing were presented. For

short-duration pulse-type motions, results demonstrate that collapsing spires can be modelled as conical rocking objects (DeJong, 2012). However, significant damage can result from two primary sources. Large rocking response can cause large residual displacements, and long duration vibration response can also cause significant displacements, even when rocking remains relatively minimal (DeJong & Vibert, 2012).

Discussion of the arch and the spire was used to demonstrate that collapse of masonry structures during earthquakes often involves the formation of a mechanism which then experiences excessive rotations. An extremely common example of this is the out-of-plane collapse of a masonry wall, which, if disconnected with perpendicular walls, can be modelled as a one-sided rocking block. There are a whole suite of structures, or structural elements, which essentially behave as rocking mechanisms of varying complexity. The derivation of equations of motion for each of these mechanisms can be mathematically complicated, and practically prohibitive. Thus, a method of deriving equivalence between any mechanism and a single rocking block was briefly presented. This involves linearizing the equations of motion, an approximation which yields relatively small error in many cases (DeJong & Dimitrakopoulos, 2014). Through such a methodology, it was proposed that the rocking response of the single block could be used to directly assess possible collapse of a large array of other mechanisms. This could be rapidly achieved for pulse-type earthquakes through rocking spectra (Dimitrakopoulos & DeJong, 2012). However, predicting rocking response for non-pulse type earthquakes is a different challenge. Code-based methods for this are discussed in Section 2, which demonstrates that these methods have their limitations.



(a)



(b)

Figure 1: Examples of rocking mechanisms for masonry structures.

## Modern Structures

After considerable discussion of rocking in the context of masonry collapse, the final part of the presentation sought to demonstrate how rocking can be beneficial, and how it may be exploited in modern design. In particular, examples of slender bridge piers were discussed, for which it is necessary to consider the flexibility of the structure itself. Analytical modelling was used to demonstrate beneficial aspects of rocking behaviour. First, increased flexibility and increased scale were shown to reduce the likelihood of overturning (Acikgoz & DeJong, 2012). Second, a wavelet-based probabilistic design method for predicting the maximum uplift of a flexible rocking structure to pulse-type earthquakes was discussed (Acikgoz & DeJong, 2014). It was demonstrated that allowing uplift and a minimal amount of rocking provides an effective cap to the force demand within the structure. However, more recent work has shown that the force demand is affected by the uplifted modal response, which is influenced by impacts during rocking motion. It is important to quantify these effects to ensure safe design, although it is unlikely that they will compromise the benefits of rocking in general.

There is also an array of work regarding rocking solutions that use post-tensioned connections within frame structures (e.g. Alexander et al., 2011), or that use rocking of frames with external post-tensioning and energy dissipation (e.g. Deierlein et al., 2011; Pampanin, 2012). Continued research aims to produce related analytical models, which could enable better understanding of higher mode response and expected force demand for these structures.

## 2. Presentation Follow-up: Code Methods for Predicting Maximum Rocking Response

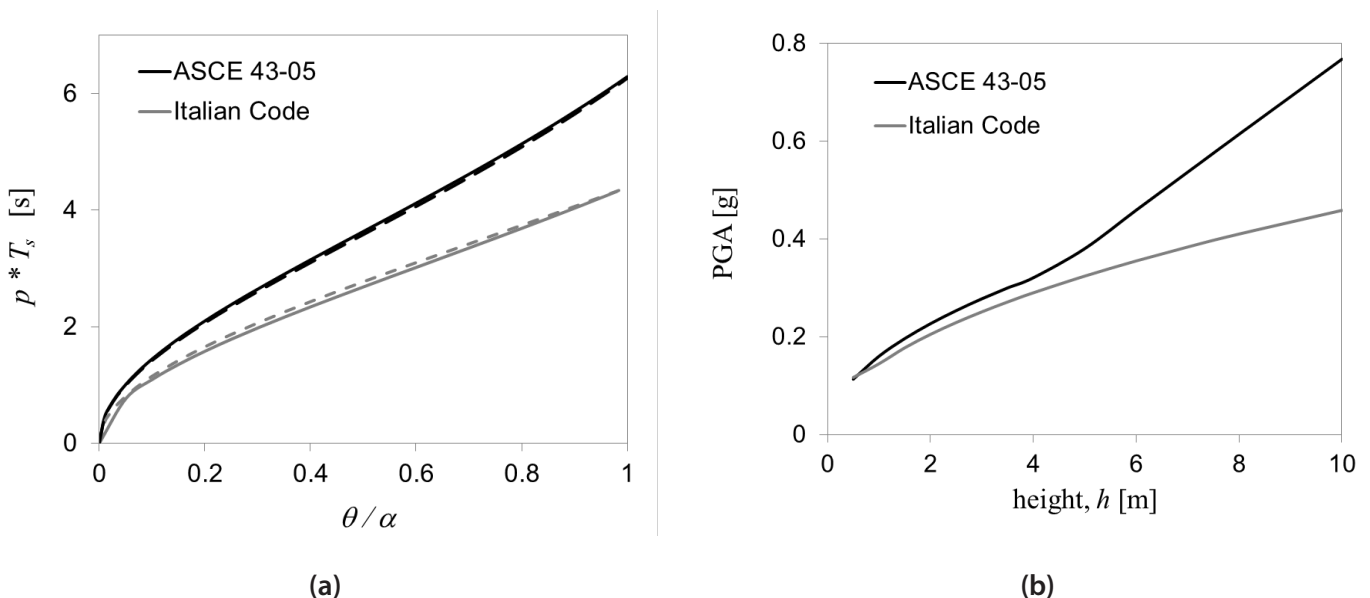
For the assessment of existing masonry structures or for modern design, an essential step is the prediction of the maximum expected rocking rotation. In many cases where structures are not excessively large, the assumption of rigid body rocking is appropriate. Expected elastic (or inelastic) displacements of the structure could be considered through the flexible rocking model mentioned above, or through computational modelling methods.

If rigid body rocking is assumed, and if practical rocking mechanisms can be described using an equivalent single rocking block (DeJong & Dimitrakopoulos, 2014), then the critical step is to predict the maximum response of the single rocking block to an earthquake. For pulse-type motions, this can be done very rapidly using analytical methods, as mentioned above. However, for non-pulse type earthquake motions, the sensitivity of the rocking response presents a challenge. In response to post-presentation discussion, this section compares two code-based procedures for predicting maximum response that do not explicitly account for pulse-type ground motions.

### ASCE 43-05

In the context of the design of nuclear facilities, ASCE 43-05 (2007) prescribes two methods for predicting a “best estimate” of the maximum rocking response. For both methods, the “best-estimate” is to be increased by a safety factor of two for design.

*Method 1:* The first method involves time-history analysis



**Figure 2: Example comparison of ASCE 43-05 and the Italian code for rocking of a rigid block ( $b/h = 0.2$ ). (a) comparison of the effective rocking period used by each method, where  $p$  is the frequency parameter of the block and the dashed lines represent the corresponding Housner (1963) solution, and (b) comparison of the predicted PGA required to cause overturning.**

using a minimum of five earthquake records which meet the prescribed characteristics for time-history analysis in general. The rocking equations of motion are to be directly solved for each time-history, and the mean maximum rocking response from all simulations is to be taken as the “best-estimate” of rocking demand.

*Method 2:* The second method is an approximate method which utilises linear-elastic response spectra in lieu of recorded earthquake time-histories. Essentially, the method approximates the rocking system using a linear-elastic oscillator by specifying that the potential energy of the rocking structure and the deformed linear oscillator is the same at the maximum displacement. Using this assumption, the following procedure is outlined:

1. Specify the maximum rocking rotation,  $\theta_o$ .
2. Determine the spectral acceleration capacity,  $S_{a,CAP}$ , as a function of  $\theta_o$ .
3. Determine the natural period,  $T_n$ , of a linear-elastic oscillator with equivalent potential energy at the specified maximum rocking angle.
4. Use a linear-elastic spectral design chart scaled to peak ground acceleration (PGA) = 1g to determine the spectral acceleration demand,  $S_{a,DEM}$ , for  $T_n$ .
5. Determine the “best estimate” for the PGA which would cause the specified maximum rocking rotation as  $S_{a,CAP} / S_{a,DEM}$ .

Thus, the procedure results in a relationship between PGA and maximum rocking angle. Given an expected PGA, a “best-estimate” for maximum rocking can be predicted.

### Italian code

The Italian code (G.U. no. 47, 2009) addresses overturning collapse, though the method is tailored to collapse of local mechanisms within buildings, rather than the overturning collapse of rigid bodies. The code also prescribes two methods, both of which are approximate (see Al Shawa et al., 2012, for an example application).

*Method 1:* The first method is a strength-based procedure that simply specifies the maximum allowable PGA to prevent collapse as a factor (typically two) of the ground acceleration which is required to initiate uplift. This is clearly a rough approximation.

*Method 2:* The second method utilises linear-elastic response spectra and can be summarized as follows:

1. Assume that the critical displacement  $du^*$  is equal to 40% of the displacement which would cause overturning of the actual structure.
2. Approximate the free rocking period of the structure with a maximum rocking displacement of  $du^*$ . This is achieved by calculating the secant period  $T_s$  of the local mechanism at a rocking displacement of  $ds^* = 0.4du^*$ .
3. Use a linear-elastic spectral design chart to determine the spectral displacement for  $T_s$ .
4. Compare the spectral displacement to the critical

displacement  $du^*$ .

Thus, the method does not directly result in an allowable PGA, but instead provides a displacement-based check of overturning. However, an allowable PGA can be directly determined if a typical elastic design spectrum is being employed.

### Comparison of Methods

For both codes, the second methods are similar. However, a major difference lies in the approximation of an “equivalent period” of the equivalent linear elastic oscillator. For a given rotation angle  $\theta_o$ :

- ASCE 43-05 defines the equivalent period by matching potential energies. Figure 2a demonstrates that the ASCE 43-05 method (solid line) essentially defines the equivalent period to match Housner’s free rocking period for 60%  $\theta_o$  (dashed line).
- The Italian code states explicitly that the equivalent period is approximated using the secant period of the structure at 40%  $\theta_o$ . Figure 2a shows a good comparison between the Italian code (solid line) and Housner’s free rocking period for 40%  $\theta_o$  (dashed line).

A second major difference lies in the definition of what rocking angle should be used to conservatively define when collapse may occur for design:

- Using ASCE 43-05, if a design safety factor of two is employed, the allowable design rotation to prevent overturning is 50% of the critical rotation  $\theta_{cr}$ . In addition, the enigmatic definition of the spectral acceleration capacity effectively increases the allowable rotation, yielding a design spectral displacement which corresponds to approximately 66%–75% of  $\theta_{cr}$ , depending on the aspect ratio  $b/h$ .
- The Italian code specifies the allowable design rotation to prevent overturning as approximately 40% of  $\theta_{cr}$ .

To clarify the comparison, consider the prediction of overturning of a block with an aspect ratio of  $b/h = 0.2$ . ASCE 43-05 uses the free rocking period at  $0.3\theta_{cr}$  to approximate the equivalent period of the linear elastic oscillator, and defines a rotation of approximately  $0.68\theta_{cr}$  to determine when overturning occurs. The Italian code uses the free rocking period at  $0.16\theta_{cr}$  to approximate the equivalent period, and allows a rotation of approximately  $0.4\theta_{cr}$  to determine when overturning occurs.

Figure 2b shows a comparison of predictions for the two methods for a given Eurocode design spectrum. Remarkably, the methods compare quite well for  $h < 5$  m, for which both methods predict an equivalent period of the linear elastic oscillator in the intermediate period range of the design spectrum ( $0.5 \text{ s} < T_s < 2 \text{ s}$ ). For larger structures, the predictions diverge and the Italian code is considerably more conservative.

In general, these methods partially account for dynamics and for scale effects, and are thus useful. However, there

is still a need for alternative methods that are simple but do not rely on linear elastic response spectra.

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## Forthcoming Events

Date	Venue	Title	People
24/9/2014 at 18:00	Institution of Civil Engineers, 1 Great George St, London	<i>Current Trends in the Seismic Design and Analysis of Bridges</i>	<i>Speaker: Andreas Kappos</i> (City University) <i>Organiser: Ahmed Elghazouli</i> (Imperial College)
29/10/2014 at 18:00	Institution of Civil Engineers, 1 Great George St, London	<i>Investigating the Effects of Critical Velocity on the Behaviour of Railway Track at High-Speed</i>	<i>Speakers: Peter Woodward</i> (Heriot-Watt University) <i>Organisers: Andreas Nielsen</i> (Jacobs)

For up-to-date details of SECED events, visit the website: [www.seced.org.uk](http://www.seced.org.uk)

## SECED Newsletter

The SECED Newsletter is published quarterly. All contributions of relevance to the members of the Society are welcome. Manuscripts should be sent by email. Diagrams, pictures and text should be attached in separate electronic files. Hand-drawn diagrams should be scanned in high resolution so as to be suitable for digital reproduction. Photographs should likewise be submitted in high resolution. Colour images are welcome. Hard copy manuscripts are also welcome. Please contact the Editor of the Newsletter, Damian Grant, for further details: [damian.grant@arup.com](mailto:damian.grant@arup.com).

# David Key

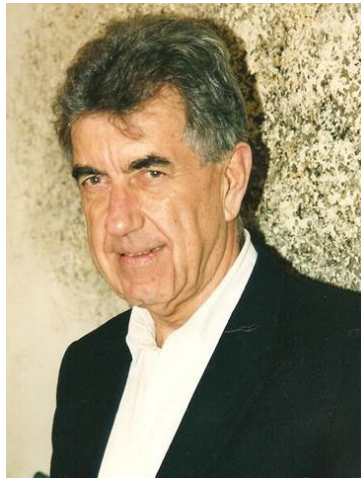
David Key died at the age of 89 in Cornwall UK on 15th June 2014. His career was focused mainly on the Caribbean and Great Britain.

David Key first went to the Caribbean for flight training in Trinidad as part of the Royal Navy Fleet Air Arm in 1943. He returned to Britain in 1944 and after the 2nd World War qualified academically and professionally as a civil and structural engineer. He returned to Trinidad in 1955 and set up an independent consulting practice. He created a ground-breaking consulting engineering family entirely with Caribbean engineers with offices in several Eastern Caribbean states.

David Key was the outstanding structural engineer in the Eastern Caribbean during the two decades of his active involvement there. His 1959 Queen's Hall is still regarded as one of the most modern structures in the region – a ground-breaking, iconic, shell structure which is depicted on a Trinidad & Tobago postage stamp. He introduced thin-shell concrete construction to the sub-region. He pioneered the sub-regional use of precast and prestressed concrete in the early 1960s and was the structural engineer for the first tall buildings in the Eastern Caribbean.

He was central to the development of earthquake engineering in the Eastern Caribbean. Along with colleagues at the University of the West Indies he produced the first, published guidance for engineers to design earthquake-resistant structures in the sub-region. When he returned to England in 1973 he used his earthquake engineering knowledge and experience, gained while working in the Caribbean, to be a seismic consultant to the UK nuclear power industry and to participate in the development of Eurocode 8. He was a Chairman of SECED in 1984–86. In his 50s he pursued and obtained his doctorate from the University of Southampton for his thesis "The Earthquake Response of Building Structures with Energy Absorbing Dampers" in 1985 dedicated to his first wife Daphne who died in 1981. He authored the book "Earthquake Design Practice for Buildings" in 1988 published by Thomas Telford. The second edition was co-authored with Edmund Booth FREng and it continues to be a standard text at the University of Bristol.

David Key's contact with the University of Bristol began in about 1986 when he was appointed a Visiting Industrial Professor. It was at this time that Profs Roy Severn and Colin Taylor were building the, then SERC, now EPSRC,



Earthquake Simulator, a 15t-capacity, 6-degree-of-freedom shaking table. The simulator opened in 1987. At that time it was recognized that seismic qualification testing would be a means to help fund the running costs of the simulator and so Bristol drew on Key's commercial and business expertise to establish BEELAB Ltd to front this industry-orientated work. David Key was effectively managing director for about 5 years. Under Key's guidance, BEELAB conducted seismic qualification tests for many UK defence and civil nuclear facilities, including Sizewell B. David gave valuable practitioner guidance as

the Department of Civil Engineering transitioned to 4-year MEng undergraduate programmes. David also contributed to undergraduate teaching through project supervision and lectures in structural engineering. David had an influential role in the development of earthquake engineering research at Bristol. He was a generous, supportive and good humored colleague who is fondly remembered.

Another of David Key's activities was the analysis concerning long-period earthquake motions and church bell ringing in the 2nd April 1990 Bishops Castle (Shropshire) event, awarded a magnitude 5.1ML eventually, and his analysis addressed this in the context of historical accounts of bells ringing in earlier earthquakes in Britain. From Prof Willy Aspinall's memory, David Key worked out what velocity or displacement was necessary for the clapper to strike the bell, taking into account the soil-structure interaction.

Throughout his career he maintained high technical and ethical standards and these are his legacy in the consulting practices that he spawned in the Caribbean. There remain four practices in the Caribbean family of firms bearing the name Consulting Engineers Partnership (CEP) – in Trinidad & Tobago (founded in 1955), Barbados (1963), Grenada (1969) and Dominica (1971). Together they comprise the largest civil/structural engineering consultancy anywhere in the Caribbean Basin. They are a testimony to David Key's success as an innovator, developer, mentor and unselfish partner in his profession as a consulting engineer. In a quiet way, he supported and encouraged the young engineers who worked with him. He had great faith in the ability of Caribbean engineers.

He is survived by his second wife Janice whom he met in 1985, daughters Wendy and Jane and son Jonathan and his four grandchildren.

– Tony Gibbs FREng, with contributions from Profs Colin Taylor and Willy Aspinall, 16th July 2014

# SECED Forum on Eurocode 8

The Structural Eurocodes, including Eurocode 8 (EC8), have now entered an extended period of revision which will result in new versions of all the Eurocodes being published in six or seven years' time. The process is a complex one, perhaps inevitably so, given the number and diversity of countries taking part. In summary, two parallel strands are involved. Firstly 'systematic reviews' are being launched, inviting national comments to be made on any aspect of the Eurocodes. Secondly an 'evolution' process will be funded by the European Commission, in which a large number of project teams chosen by CEN (the European standardization organisation) will produce revised drafts of the Eurocodes according to a work plan written by CEN, but also taking into account the results of the 'systematic reviews'.

The BSI (British Standards Institution) sub-committee dealing with EC8 is keen that there should be a strong UK voice during the revision process. It therefore asked SECED to set up an online forum to enable members of the earthquake engineering community to table and debate their views. The forum is now open to all (both SECED members and others) and is accessible from the SECED website, [www.seced.org.uk](http://www.seced.org.uk); all that is required to comment

is to register on the SECED site. There are six sub-sections to the forum, corresponding to the various parts of EC8; each sub-section has an introduction provided by its moderator, which gives suggestions for particular aspects that might be debated. Please also read the general introduction to the forum, which sets out the general parameters within which comments should be made.

The revision process will continue over a number of years, but since the process is phased, comments on some parts of EC8 are needed now. The 'systematic review' of EC8 Parts 1 and 3 has already been launched, and BSI has to give a UK response on these parts by September 2014. Reviews of subsequent parts of EC8 will follow in 2015 and 2016, but it is comments on Parts 1 and 3 which are particularly invited at this time. The 'evolution' process has yet to start for EC8, or indeed any of the Eurocodes, but it is hoped that, despite the slow pace of European bureaucracy, it will be underway for Parts 1 and 3 by early next year.

The forum is now open for comments and already a live-debate has started. Please consider joining it and helping make EC8 an internationally leading standard fit for 2020 and beyond.

## Eurocode 8 and the Building Regulations of England and Wales

An article in the last issue of the SECED Newsletter reported that, for the first time, the Building Regulations have recognised that, in certain circumstances, seismic loading may need to be considered when designing buildings in the UK. This is a significant milestone, especially since it applies to one of the least seismically active countries in the world. It should however be realised that the requirements quoted from the Building Regulations are taken from BSI (British Standards Institution) documents published some time ago. The UK National Forewords to Eurocode 8 (EC8), published ten years ago, state:

*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 EN 1998 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.*

The 'background information' referred to in that last sentence was subsequently provided in a BSI document, PD6698, published in 2009; this is also referred to in the

UK National Annex to EC8 Part 1.

As well as giving guidance on the National Annexes, PD6698 provides a general discussion on the circumstances in which seismic loading may need to be considered in the UK. The following general statement is made:

*It is the responsibility of the designer to establish whether statutory or other considerations require an explicit seismic design. In the absence of statutory requirements or contractual specifications, structures classified by BS EN 1990:2002, Table B1, as being in consequence classes CC1 or CC2 are unlikely to warrant seismic design, provided they are adequately designed for non-seismic design conditions.*

For structures in consequence class CC3, the need for an explicit seismic design should be considered, although in many cases examination of the consequences of failure, location and structural form will indicate that an explicit seismic design is not warranted.

It is safe to assume that the time when seismic loading needs to be considered in the design of a four bedroom semi in Tring (or anywhere else in the UK, for that matter) is some way off yet.

– Both items contributed by Edmund Booth

# SECED Website Developments

The SECED website continues to play a small, but useful, part in the life of the Society. It evolves slowly and without the support of any professional website designers or other administrative staff, thus keeping costs as low as possible. This article outlines some of the recent developments.

One of the key functions of the website is provide access to the older volumes of the SECED Newsletter. At the moment, the website contains a partial catalogue of downloadable Newsletters, reaching back to volume 15 published in 2002. The aim is to provide a full catalogue of all volumes, from the first Newsletter published in 1987 to the latest issue, but the indexing of Newsletter articles is a slow process. In the meantime, should any member of the Society wish to obtain a PDF copy of one of the older volumes, please contact the current website administrator (contact details below).

The website is also used to disseminate information about our evening meetings. In the first instance, evening meetings are advertised on the website. The online adverts contain the most recent information on each meeting, including synopsis, speaker biography, and other details of

more practical nature. Once the meeting has taken place, we usually ask the speaker to provide a copy of the slides. Although some speakers may wish to redact the presentation prior to online publication, in many cases a full set of slides is provided. The presentations are then uploaded to the 'Resources' section of the website, under 'File sharing'. Finally, each evening meeting is usually recorded, and the recording is subsequently made available online for viewing. Links to the recordings, which are not hosted directly on the SECED website, can be found in the 'News' section.

As described elsewhere in the present Newsletter, the website is also host to a new Eurocode 8 forum. This forum is open to all, SECED members as well as those who for some reason or another have not yet joined the Society. The only prerequisite is registration on the SECED website.

Should you have any queries regarding the website, or if you wish to advertise an event of interest to the members of the Society, please contact the current website administrator at the followings email address: andreas.nielsen@jacobs.com.

– Contributed by Andreas Nielsen

The screenshot shows the SECED website's Eurocode 8 forum. At the top, there is a navigation menu with links for Home, Events, News, Resources, About SECED, SECED 2015, and EC8 Forum. Below the menu is a search bar and a login section for 'Guest' users. The main content area features a 'Welcome to the SECED forum for Eurocode 8' message, followed by a table of forum topics. The table lists various parts of Eurocode 8, such as '1a. Part 1: General rules (non-material specific)', '2. Part 2: Bridges', and '7. Maritime structures'. Each row in the table provides the number of topics and replies, along with the date and author of the last post. At the bottom of the forum page, there are statistics for the forum, including total messages, subjects, sections, categories, and users.

Topic Name	Topics	Replies	Last Post
1a. Part 1: General rules (non-material specific) Moderators: Damian Grant	5	16	Last Post: 3.2.2.2, 3.2.2.3 des... by Chris Rogers 1 month 5 days ago
1b. Part 1: General rules (material specific) Moderators: Ahmed Elghazouli	0	0	No Posts
2. Part 2: Bridges Moderators: Andreas Kappos	0	0	No Posts
3. Part 3: Assessment and retrofitting Moderators: Andreas Kappos	0	0	No Posts
4. Part 4: Silos, tanks and pipelines Moderators: Edmund Booth	1	1	Last Post: Clause 2.1.4(4) by Edmund Booth 1 month 1 week ago
5. Part 5: Geotechnics	2	0	Last Post: Annex E (Normative) by Milutin Brulov 2 months 1 day ago
6. Part 6: Towers, masts and chimneys Moderators: Edmund Booth	0	0	No Posts
7. Maritime structures 🏗️	0	0	No Posts

Screenshot of Eurocode 8 Forum on SECED website.