13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 214

IDEERS - An International Competition to Design Earthquake Resistant Model Buildings

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SUMMARY

Since 2000, members of the Earthquake Engineering Research Centre (EERC) at Bristol University have been running an international competition to design earthquake resistant model buildings. The competition was originally developed to educate UK school students about the effects of earthquakes on structures and to help them investigate and develop solutions to a simple design problem. However, the competition is now also being used in Taiwan and Japan to help enthuse and educate High School students, University students and the general public about the principles of good engineering design for earthquake resistant structures. Many different, and often innovative, structural solutions to the problem have been developed by students over the last four years and some of the more unusual solutions are presented here. This paper also compares the different styles of design created by students from the different countries. It is hoped that use of the competition in countries at a higher risk from earthquakes will increase general awareness of the importance of good design and help reduce the likelihood that inappropriate structures are built where there is a risk of earthquakes.

INTRODUCTION

Earthquakes have a significant effect on society causing the loss of infrastructure and life. However, there is still a lack of general public understanding into the way that earthquakes affect structures and the preventative measures that can be taken to design safer structures. If more people were aware of the factors affecting the performance of structures and the importance of good design and construction, then this might reduce the likelihood that inappropriate structures are built where there is a risk of earthquakes. Whilst the larger engineered structures will always require specialist engineering design input, the general public has significant influence over smaller construction such as housing. Therefore, by increasing general understanding of the risks of poor construction in earthquake prone regions, it may be possible to mitigate some of the effects of earthquakes in the longer term.

In order to increase public understanding of earthquake engineering and inspire children, some of whom who may become the engineers of the future, a web-based project has been created to promote

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understanding of the value and process of earthquake engineering activities. The website describes the effects of earthquakes on communities, the need for research to improve the earthquake resistance of structures, and the fundamentals of the seismic behaviour and design of earthquake resistant buildings. The website (http://www.ideers.bris.ac.uk) also provides details of a competition requiring the design and construction of a model of an earthquake resistant building [1].

Since the start of the project, over a thousand students, between the ages of 12 and 25, have built and tested models their models to destruction on earthquake simulators around the world. Posters produced by the students have shown that, through participating in the project, they have come to understand the importance of earthquake engineering activities and have learnt a number of the basic principles of good seismic design and construction.

DEVELOPMENT OF THE COMPETITION AND WEBSITE

The IDEERS challenge to design and build an earthquake resistant model building was developed in several stages, starting with the initial conceptual design. It was developed through pilot trials in the UK with schoolchildren and undergraduates before the first national UK competition was launched. The key requirements for the models were based on the following criteria:

- Models must be representative of real structures.
- The competition rules must be flexible enough to allow a large number of different designs.
- It must be possible to test and destroy models using a typical shaking-table so students can observe failure modes and compare the ultimate performance of their models.
- Materials for models must be cheap and readily available to schools.
- No special equipment must be needed to construct the models.
- The model making skills needed must suit the target age group.

The use of cheap materials, and the ability to destroy the models on a typical shaking-table, within its performance limits, drove much of the design development. The final list of materials allowed in the construction of the models is:

- Strips of medium density fiberboard (MDF), with cross-sectional dimensions 6 mm x 4 mm.
- Sheets of paper.
- String.
- PVC hot melt glue sticks.
- A single square MDF base for the model 25 cm square and 5 mm thick, drilled with up to sixteen 8 mm holes to fix the model to it.
- Plasticine.
- Plastic or steel ball bearings.

This set of materials has allowed students to build a very wide range of models. The MDF strips are mainly used for the structural columns and beams. The sheets of paper can be used as floor plates and also as shear walls. The string can provide very light tension bracing but has also been used by several students to strengthen joints or wrap columns to enhance the strength of the MDF strips. The plasticine and ball bearings have been used to introduce damping elements or isolation systems into the structures.

To cater for the range of student abilities across the age groups being considered, the final rules for the structures had to be relatively simple to understand, but flexible enough to allow for innovation. The authors' aim was to devise a set of rules that would result in the construction of models of realistic buildings. However, the number of rules also had to be kept to a minimum to avoid confusion. This resulted in a specification that:

- placed limits on plan dimensions.
- specified floor area and mass per unit area of floor to be carried at each level (10g/cm). This keeps the natural frequencies of the models down and creates sufficient inertia forces during the shaking table testing to destroy the models.
- specified that a minimum of 50% of the external face of the building be clear of bracing to allow for window and door openings. This prevents the construction of very strong box-like structures that could not be destroyed on a shaking table.
- limited the materials that could be used.
- placed limits on cross-sectional area of framing elements, gauge of paper, ply of string.
- defined minimum vertical and horizontal load carrying capacity.
- outlined the characteristics of the simulated earthquakes to be used in final competition.

In order to fully explain the competition rules, a website [1] was developed in parallel with the development of the competition. The style of the website is kept simple and visitors to the site can drill-down through the various pages to get to their desired level of detail without getting swamped by too much information irrelevant to them. Although the detailed theory behind any seismic design has not been included on the site, the basic science and engineering is carefully explained, Crewe et al. [2]. In a few cases where it is necessary to do detailed analysis/design calculations, automated scripts have been incorporated in the website. These scripts take information about a students' model and then provide answers to calculation that would be difficult for students to perform by hand. An example of this is the conversion of the dynamic forces that the models will experience during the shaking table testing into equivalent static forces that can be used by the students to test and develop their models. Information about the properties of the student's models is fed to the calculation using the forms shown in figure 1.

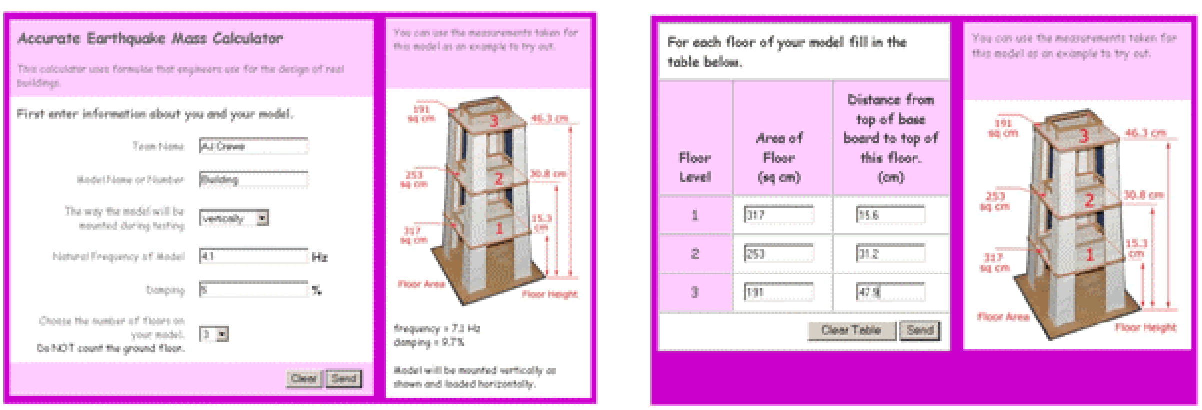

Figure 1: Data input screens for the "Earthquake Mass Calculator" pages.

Using this information, the calculation used is based on a standard push-over force calculation where:

D = Ductility of model (assumed to be 1.5)
ζ = Measured damping ratio (or assumed to be 4%)
f = Measured natural freq (or assumed to be 3Hz to 5Hz)

S_g = Spectral Acceleration, is calculated from f and ζ using the "design" time history which the models will be subjected to on the shaking table (or is assumed to be 3g in the absence of detailed dynamic characteristics of the model).

A modification to the loading calculation is then made based on the direction in which the model is to be mounted for static testing and taking an assumed ductility of the materials. Two possible static loading scenarios are shown on the website. In the first case, the model is loaded with the appropriate vertical floor loads, and using string running over a set of pulleys, horizontal loading is applied to the structure. This is representative of the true loading that will be applied during the shaking table testing but is difficult to set-up. Therefore an alternative system is suggested, where the model is mounted horizontally with the horizontal loading applied by attaching masses at each floor level. This system does not allow the vertical floor loading to be applied simultaneously so it is not quite as accurate as the first method.

The modification made for the loading direction and ductility:
if the model is to be mounted vertically (with floor loads on each floor) and then pulled sideways:
$S_d = S_g /D$
if the model is to be mounted horizontally (no floor loads on model) and then pulled down:
$S_d = S_g/D - 0.2$

The calculation of the equivalent horizontal forces then proceeds as follows:
W = total of masses applied to all the floors
Base shear $F_b = S_d \times W$
Horizontal force at a floor $(F_i)=F_b[(Z_i \times W_i)/(\sum(Z_i \times W_i))]$
where Z_i = height of floor from base
and W_i = mass on the floor

Typical results from the calculation above are shown in figure 2.

Earthquake Mass Calculator - Results			Wed 25 Feb 2004
	Team Name	AJ Crewe	
	Model Name or Number	Building	
Floor Level	Area of Floor (sq cm)	Distance from top of base board to top of this floor. (cm)	Mass required for Earthquake Load Test (kg)
1	317	16	2.931
2	253	31	4.544
3	191	48	5.276

Total Mass required for the earthquake load test = 12.751 kg

Mount your model vertically and apply these loads horizontally to see if your building should survive the earthquake

Figure 2: The calculated push-over results for static testing of a model.

THE IDEERS CHALLENGE

The IDEERS challenge originally had two parts. In the first part of the competition, the students accepted for the national finals had to prepare and present a poster to the judges outlining how they had developed their models and what they had learnt about the importance of earthquake engineering to society. The students who produced the best poster and made the best presentation won a prize for the "best presentation". Secondly, the students' models were mounted on the shaking table and subjected to a series of modified sine sweep shakes of varying amplitudes, see figure 3.

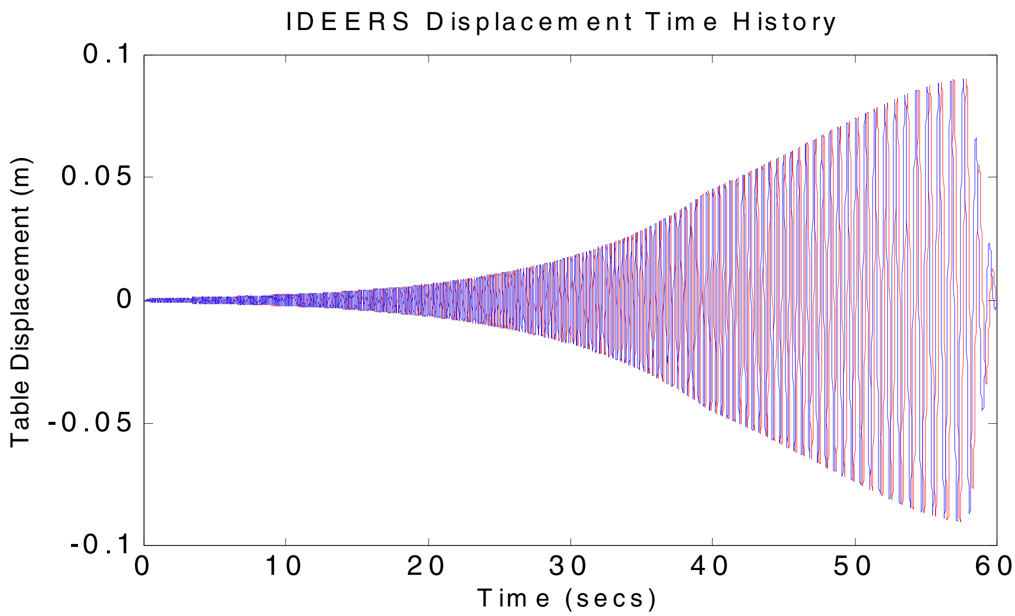

Figure 3: The bi-axial "design" displacement time history used for the IDEERS competition.

Sine wave motions were used so that the behaviour of models could be more easily understood by the students. As the shake progresses, the natural frequencies of each for the models can clearly be seen and compared. The second motion, 90º out of phase with the initial motion, was designed so that if the two are used in the horizontal X and Y axes of a shaking-table simultaneously, the resulting motion is circular. This circular motion was created so that models would be subjected to earthquake motion in all directions. Therefore, students had to think about providing stiffness along all axes of their model to avoid a soft storey failure in one direction. In the pilot competitions, some students created models with only one stiff axis, to align with the direction of the single axis input motion. The use of a circular motion therefore encouraged more realistic design solutions with stiffness in all axes.

The first shake is always set at a very low level (5% of the design earthquake which results in a 0.014g peak table acceleration) so that all the models survive. In this way all the students competing gain some satisfaction that their models can survive at least a small earthquake. Then the size of the input motion is increased in constant steps from 10% of the "design level" earthquake up to 400% of the design earthquake (peak table accelerations of at least 1.12g). After each shake any models that have collapsed during that shake are noted and the previous earthquake is recorded as the largest earthquake that they survived. This earthquake size is used to calculate the model's efficiency ratio (see eqn 1). Prizes are then given for the "most efficient" models.

$$Efficiency\, ratio = \frac{Size\, of\ max\ earthquake\ survived}{mass\, of\ model\ including\ penalties} \qquad \text{eqn 1}$$

The use of a penalty system was introduced early in the development of the competition when it became clear that not all students were able to built sufficiently accurate models. In many cases the design was well thought out but, during the building of the models, mistakes were made and this would result in structures that did not meet, for example, the minimum floor to floor height. So that these students would not have to be disqualified for not meeting the specification of the model, a penalty system was introduced to penalise models that made minor infringements of the rules.

NATIONAL COMPETITIONS

IDEERS was originally designed to run as a national competition for school children in the UK. The competition was very successful and many schools took part. However, following discussions with teachers it became clear that the format of the competition did not fit in as well as hoped with existing workloads for school teachers which had resulted in a reduced number of entries. It was also noticed that all the schools entering were from the South West of the UK generally within 50 miles of the University. Whilst there had been a great deal of interest from throughout the UK, the cost of travel, which could not be covered by the University, was a significant deterrent to schools further from the University.

At this point, there was also a significant development of the competition when the authors were invited, by the British Council, to run IDEERS in Taiwan for University students. In Taiwan, the competition was run as a single day event and this format has subsequently been used in the UK. IDEERS now runs as an annual one-day design, build and test event in the UK, in conjunction with @Bristol, a local science centre. The event is now based around a single day of activities and has proved very popular both with the teachers and the students taking part. The single day format, in particular, has proved easier for teachers to incorporate within a school timetable than several smaller design and build sessions. Before the day of the competition students can make use of the web site to research some of the techniques used to make earthquake resistant buildings and can plan their design. Then on the day of the competition all the models are built and at the end of the day the models are tested. The use of posters as a pre-qualifying stage to the competition is not necessary when the competition in run in this format and has now been dropped.

The collaboration between the University and the @Bristol Science Centre has been beneficial to both parties. @Bristol has strong links with regional schools and the EERC has been able to exploit these and hence get more people interested in engineering. The University's expertise and test equipment has also been made available, through the competition, to the @Bristol staff who have subsequently been able to provide a more interactive experience and inform more of their visitors about earthquake engineering. The initial links through the British Council have also been developed, and IDEERS has now become an annual event in Taiwan and it is hoped that the competition is having a significant impact educating the general public there about the research and activities of the earthquake engineering community in their country.

INTERNATIONAL COMPETITIONS

Since 2000, the IDEERS competition has been run four times outside the UK. The competition has been held three times at the National Centre for Research in Earthquake Engineering (NCREE) in Taiwan on the anniversary of the 921 Chi-Chi earthquake. Some of the posters and brochures that have been produced to support the event in Taiwan are shown in figure 4. In Taiwan, the competition has generated significant press and TV publicity, and in 2001 a one hour TV programme about the competition was produced for broadcast on National Taiwan Day. The TV programme combined the excitement of the competition with a more serious discussion about how earthquakes cause damage to structures. The programme referred particularly to the damage after the Chi-Chi earthquake which was still fresh in people's memory, and by including information about the technical side of earthquake engineering design it will have helped to educate the general public about the need for good engineering solutions to meet the challenge of earthquake resistant design. Following the success of the competitions in Taiwan, in 2003 the competition was held for the first time in Japan at the Kajima research laboratory in Tokyo, and some of the publicity is shown in figure 5. It is hoped that there will be many further events in Japan and other countries in the future.

Figure 4: Some of the publicity for IDEERS events in Taiwan.

Figure 5: Some of the publicity for IDEERS event in Japan.

The competitions themselves have been extremely popular, and since 2001 NCREE has run parallel competitions for High School and University students from all over the country. This has resulted in intense competition, and by displaying all the models before testing starts, figure 6, there has been an opportunity for high school students to learn from the more complex University students' designs, figure 7. The NCREE laboratory has also been opened to the general public during the competition. Banners displayed outside the laboratory have led to many casual visitors visiting the laboratory during the competition, simply to see what is going on. This sort of activity helps to give a much broader cross section of the public some insight into work going on in research laboratories. There have also been several instances of families with young children visiting NCREE during the competition, see right figure 6. These young children have always enjoyed the destruction during the shaking table testing, figure 8, and many have expressed a desire to take part in the competition when they are old enough.

Figure 6: Some of the models created by High School students in Taiwan.

Figure 7: Some of the models created by University Undergraduates in Taiwan.

Figure 8: Some of the Taiwanese models being tested on the NCREE shaking table. Note the large sway deflections in several of the softer models.

Another effect of the intense competition that has been generated by these events has been the development of a much more comprehensive set of failure criteria. In the initial competitions run in the UK, the judges determined when a model had failed, as no failure criteria had been defined. However, in a few cases, where models were judged to have failed (e.g. when the steel blocks used to apply the vertical floor loads to the structure had fallen out of the building), students were unclear as to why this decision had been made. Consequently a specific set of failure criteria was produced, with the reasoning behind each one, and these rules have been used in all the international competitions:

- Soft storey failure of one or more floors: This is a failure mode seen in many real buildings, often leading to fatalities as people are crushed between floors and a typical failure can be seen on the right of figure 8.
- Steel blocks falling out of structure: When blocks fell out, the effective force on the model was reduced, which gave an unfair advantage over other models with their full complement of blocks. To make the competition fair, this had to be considered as a failure.
- Steel blocks no longer connected to the structure, and able to slide or rock: Again this was introduced to stop some models gaining an unfair advantage over others, because if the blocks were allowed to move, the effective force on a model could be dramatically reduced. However, in one competition, one team developed a floor isolation system where the blocks were connected to one section of floor that could slide over another part of the floor. This was allowed as it was a properly designed isolation system, and additional materials had to be used to create the complex floor.
- Rocking of the model: This failure mode was introduced after one competition where the columns of the wining model were loosely tied to the baseboard with a short piece of string allowing the model to rock by up to 30º from the vertical. Whilst a sliding isolation system was allowed within the competition, as this is a technique often used for real structures, no real structure would be allowed to rock in such a way, so in subsequent competitions rocking was considered as a failure.
- Failure of more than 50% of the columns at base level: This failure mode was introduced as a simple way of detecting whether a building was rocking. An example of a building where the columns have failed at the connection to the base board can be seen on the left of figure 8. In this case the failure has led to toppling of the structure.
- Any other failure that the judges consider would be unreasonable in a real building: Experience of many IDEERS competitions has shown that it is difficult to anticipate how the designs produced by the students will perform, so this failure rule was introduced to allow the judges to fail any model which they agree would be unsafe, if it were a real structure.

Figure 8: Typical failures observed during the shaking table testing.

COMPARISON BETWEEN MODELS PRODUCED BY STUDENTS FROM DIFFERENT COUNTRIES

Over the many years that the competition has been running, a great number of different designs have been produced by the school and university students. Of particular interest are the fundamentally different design styles of the three counties and the very different ways that the models fail. The main differences between the models probably stem from the different types of construction that the students see around them every day. Most models made by UK students have strong floors and relatively weak columns (left figure 10), because earthquake loading is not normally a key design case in the UK, where the seismic risk is low. The models made by the Japanese students (right figure 10) and Taiwanese students (figure 11), however, follow standard earthquake engineering practice, having strong columns and weaker floors. Another obvious difference is the way Taiwanese students use a great deal of string to wrap their columns and beam/column joints to enhance their strength (figure 11), this is very different to UK students who rarely use string in their models. It is not clear why Taiwanese students like to wrap the beams and columns of their models with string, but it could be because much of the post Chi-Chi retrofitting of bridge and building columns has been accomplished using concrete or steel encasement techniques.

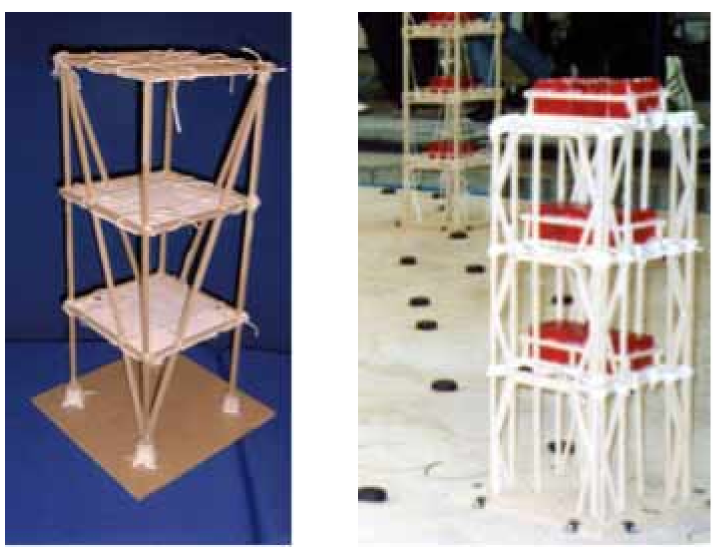

Figure 10: Typical UK (left) and Japanese (right) students' models.

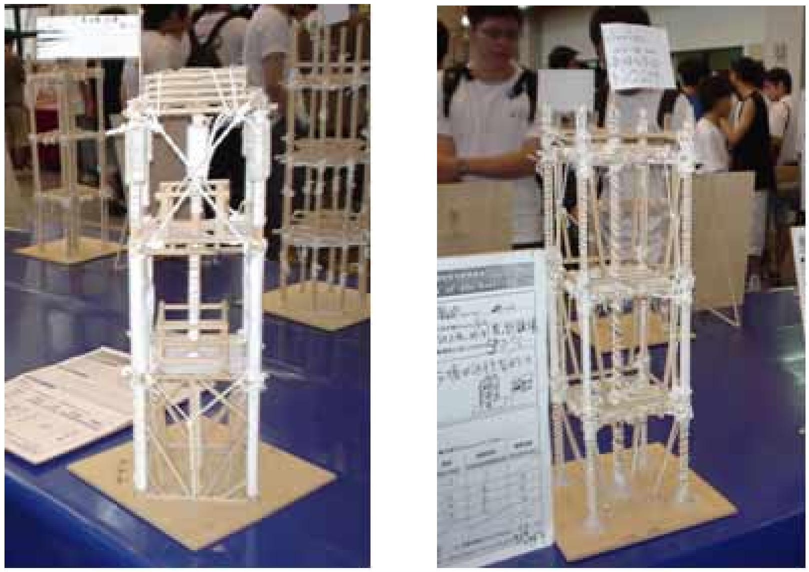

Figure 11: Examples of wrapped columns and connections strengthened with string.

The Taiwanese students also use the concept of mega-trusses (left figure 12) which are the form of construction used in the very tall Taipei 101 building. An unusual solution to the design problem that has been tried, successfully, by Japanese students is the use floor isolation. A building incorporating this feature is shown right figure 12. The student is holding one of the moveable floor sections that will later be incorporated in their building. Connected to the floor that has already been fitted, it is possible to see the string that had been used to limit the overall displacement of the floor. It should be noted that this model has not yet had much bracing added to the frame. The main bracing was added once the isolated floors had been installed in the structure.

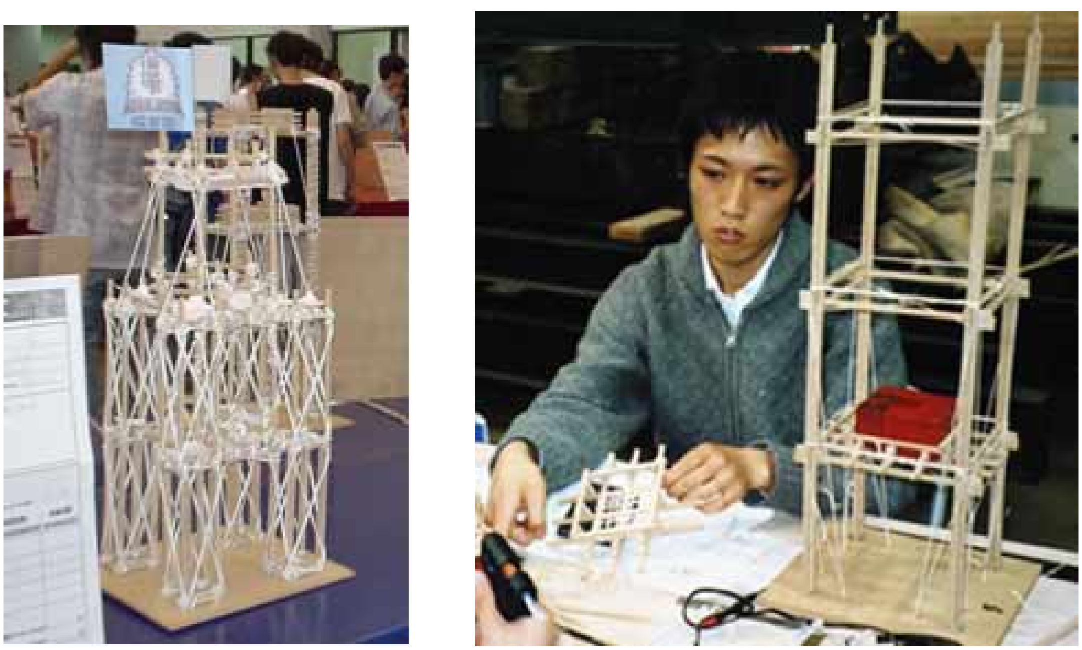

Figure 12: Taiwanese model incorporating mega-trusses (left) and Japanese model incorporating a floor isolation system (right).

The different forms of construction also resulted in different failure modes. Typical failure modes include:

1. Soft storey failure in lowest storey, see right figure 8.
2. Soft storey failure in one axis because no bracing was included in that plane. An example of a model likely to fail in this way can be seen left figure 11. The middle storey in the building has no bracing in one axis of the building.
3. Soft storey failure where there is a change in stiffness of the model, generally caused by a change in floor dimensions. An example of a model likely to fail in this way can be seen left figure 12. There is a significant change is stiffness between the 2nd and 3rd floor levels.
4. Lack of rotational stiffness leading to a failure of the whole structure in a twisting mode.
5. Joints coming apart because the model was badly constructed.
6. Toppling of whole structure when connection to base board fails, see left figure 8.
7. Compression failure of long columns.
8. Additional masses falling from models because their support frames were not sufficiently robust. Likely to happen to the model shown left in figure 10.

In summary, all of the typical failures of real structures after real earthquakes have been observed in the students' models. To best explain the failures seen during the tests, wherever possible consulting engineers working in structural dynamics have been used as judges as well as researchers from the Universities or research laboratories. After each test the judges have talked about the failure modes observed during the tests. This has helped to educate the students who have taken part in the competition and when students have taken part in subsequent years their models have improved significantly taking the previously observed failure modes into account.

CONCLUSIONS

Over the last five years, IDEERS competitions have generated a significant amount of interest world-wide and it is hoped that the project has and will continue to inspire and educate some of our future engineers about the importance of earthquake engineering activities. The activities have been valuable for society at large, but the competitions have also been of great benefit both the researchers at Bristol and the other institutions where the competitions have been run. The competition has exposed overseas students to researchers at Bristol University and it is hoped that some will have been inspired by the competition and consider coming to the UK to study. The competition has also resulted in the creation of an academic link, to foster collaborative research, between NCREE and Bristol. Although many of the benefits from activities such as this are hard to quantify, it is becoming increasingly important for researchers to be involved in public awareness activities, and competitions like this can provide an enjoyable way for researchers to engage with the public and at the same time develop links with similar organizations around the world.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the EPSRC who have provided the financial support for developing this project, Prof. Rosamund Sutherland for her expert advice on the educational aspects of the website, Tony Gee and Partners, AEA Rail Technology, Lloyd's Register and Mott MacDonald for their sponsorship of the Taiwan challenge, the British Geological Survey, and Alice Walker in particular, for their assistance with the website. The authors also thank the British Council in Taiwan and Japan, and the laboratories at NCREE and Kajima who have supported the development of the competition overseas.

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