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ROBUST FRICTION BUILDING SHAKING TABLE TESTING OVERVIEW

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ABSTRACT

Shaking table testing of a full-scale three storey resilient and reparable complete composite steel framed building system is being conducted. The building incorporates a number of interchangeable seismic resisting systems of New Zealand and Chinese origin. The building has a steel frame and cold formed steel-concrete composite deck. Energy is dissipated by means of friction connections. These connections are arranged in a number of structural configurations. Typical building non-skeletal elements (NSEs) are also included. Testing is performed on the Jiading Campus shaking table at Tongji University, Shanghai, China. This RObust BUilding SysTem (ROBUST) project is a collaborative China-New Zealand project sponsored by the International Joint Research Laboratory of Earthquake Engineering (ILEE), Tongji University, and a number of agencies and universities

within New Zealand including BRANZ, Comflor, Earthquake Commission, HERA, QuakeCoRE, QuakeCentre, University of Auckland, and the University of Canterbury.

This paper provides a general overview of the project describing a number of issues encountered in the planning of this programme including issues related to international collaboration, the test plan, and technical issues.

1 INTERNATIONAL COLLABORATION

1.1 Opportunity for Collaboration

Collaboration was possible on this project because the government of China decided to establish the International Laboratories of Earthquake Engineering (ILEE). As part of this, they agreed to open up their high performance laboratories to researchers from around the world. These researchers work together with Tongji staff members to address key research topics in earthquake engineering. To further facilitate this collaboration, financial support for such activities is available in a number of ways. The most significant support is 2:1 matching of overseas funds up to a specified limit. A number of ILEE collaborative projects have already been conducted.

New Zealand researchers were made aware of the research opportunity by Dr. Tony Yang of Tongji University, the current ILEE director. He visited NZ several times during 2016 and 2017 and described the opportunities for collaboration. As a result, the RObust BUildings SysTem (ROBUST) Project, involving shaking table tests on a full scale 3 storey steel structure with friction connections was initiated for the testing of friction frames with NSEs to make a complete resilient building system. New Zealand organizations were asked if they were willing to be involved, and seven have signed up to date. These include: BRANZ, HERA, QuakeCentre, QuakeCoRE (the ILEE partner organisation based at University of Canterbury), EQC, and the University of Auckland. Comflor is also kindly supplying material. These organisations exceeded the minimum funding (equivalent 500,000RMB) required to fully access the 1,000,000RMB available (with the 2:1 matching), of which ILEE provided 600,000RMB and Tongji University 400,000RMB.

The researchers involved with the project include the coauthors of the paper, plus about 14 students at Chinese and NZ institutions. In addition, there are a number of research advisors in NZ, China and other countries.

After significant discussions about how to transfer NZ$ to China, the contracts were drawn up and signed, bringing the ROBUST project to life.

1.2 Benefits of Collaboration

Because New Zealand has led the research, development and implementation into practice of seismic friction sliding connections, there were initially suggestions that New Zealand should capture this technology, so as to give NZ a competitive advantage, or an opportunity to even export technology or whole buildings. However, the argument on the other side was that the technology already developed regarding asymmetric friction connections, symmetric friction connections, and the GripNGrab devices was already developed and available in the public domain. Some had been developed, and widely published, with steel industry funds, but much had also been developed with governmental funds or general industry funds. The fact that it was in the public domain was one of the reasons that friction technology has been implemented in a number of buildings around New Zealand. There are therefore no secrets with the technical issues.

Some concerns were also raised about the sharing of ideas with mainland China. This arose out of concerns about prefabricated steel being imported into NZ and undercutting NZ fabrication shops. However, the experience has been that for good quality fabricated steelwork, costs are not significantly different to those in

NZ, and the transportation of these items to NZ increases the costs to above the NZ levels. Imported fabricated items used in NZ are usually only the larger sections (such as large rectangular tubes) which are not possible to fabricate in NZ and the experience has been that good quality imported fabricated steelwork is of similar standard to that made in NZ. For these reasons, there was no downside in working closely with mainland China on this project and considerable potential mutual benefits.

There were questions about the use of any patentable IP developed during the ROBUST programme. However, this was determined by ILEE policy, that there would be no patents from either side developed as a result of ILEE testing. This approach was also consistent with the philosophy of the leadership team members from New Zealand and China.

It was recognised that there were excellent researchers both in China and New Zealand. Because of the different approaches, it was possible that both countries would equally benefit by working together. The benefits to NZ were the opportunity to test a large building system (even more than a structural system), of full scale, with a range of friction devices and NSEs at relatively low cost. This would demonstrate the efficacy of steel structures of the sort studied, as well as the NSE details. This was not possible with the very limited earthquake engineering facilities available in New Zealand. Also, international uptake of steel structures, using these, or other systems, would be beneficial to the NZ steel industry as part of their advertising. The benefits to China are the experience of working with an experienced research team from a steel intensive country with high seismicity and being able to get one of their proposed low damage systems (rocking column) tested in a cost and material effective manner. Seismic performance of widely employed details for glazed curtain walls (GCW) in China and newly proposed GCW with rocking details can also be verified. Weekly discussions also benefit Chinese researchers in improving the details of the self-centring frictional joints of the rocking column.

1.3 Quality Control

Quality control is essential for any project, and there had been some major issues with Chinese steel reported in the New Zealand newspapers. The NZ side initially considered that the frame would be constructed in NZ, preassembled, disassembled, shipped to Shanghai and assembled for testing there in the Jiading labs. However, the time and cost associated with such an approach, especially considering the high likelihood of import taxes, was prohibitive. It was also recognised that some of the world’s best construction, requiring the world’s highest standards for quality, such as the Hong Kong-Zhuhai-Macao bridge, also was developed fully by China and that good quality Chinese structural steel construction is available. The key issue has been ensuring that the suitable quality control procedures and personal are in place and the local knowledge of the Chinese members of the research team is key to this.

As part of this project, several steel fabricators have been considered, and one known for good quality control personal and systems has been selected. In addition, independent inspection by group members is being provided, in the same way as that required in any country. Also, several suppliers of different NSEs have been considered. While some were willing to assist, their head office indicated that spending time on this public domain research, was not a priority for the company, and even if they were paid to do the work, the work involved was too small for them to make money. As a result, a number of discussions were held to find companies that considered the work important enough to perform, and who would make the work a priority with experienced employees.

1.4 Trust

One of the biggest issues when conducting collaborative research is trust, especially if the collaborators are previously unknown and the physical work is being undertaken in China on all the proposed systems. In this project, trust has been developed because collaborators on both sides were willing to communicate freely and honestly. Weekly meetings were held. The number of formal weekly meetings held by 4 January 2020 was 84. These meetings allowed everyone to see the overall progress, to cross-check analysis results, and ensure compatible details. These were held in addition to many other informal meetings discussing specific issues. Furthermore, the NZ project leader, MacRae, spent most of 2019 at Tongji University working with the collaboration group. This also facilitated honest discussion, and the pathway for communication between the research teams from the two countries. In addition, it is of great importance to have some capable overseas Chinese students who are studying in NZ involved, since there may be some misunderstanding among team members due to differences in languages and culture. It is also critical for these students to be able to communicate with technicians of Tongji labs effectively.

1.5 Administration

For a project involving many sponsors, and two countries, significant administration is required. With a large team (9 sponsors) and over 30 researchers and advisors, it is important to have a project manager who is familiar with the technical details, as well as a technical administrator, whose job is to respond appropriately to sponsors, and fill in the large amount of paperwork required.

Sponsorship: The ROBUST team are grateful to ILEE and Tongji University who provided the largest funding for this project. One initial role was to ask potential sponsors in NZ for support. Many of those, with an interest in making NZ a better and more resilient country connected to steel structures, general earthquake-related research and applications, and NSE issues, responded to this appeal and became donors. They are noted in the acknowledgement section at the end of the paper. MBIE, who had supported a similar concrete structure test on the ILEE labs with a NZ $200,000 funding, after a number of requests, has to date not taken the opportunity to support this research with steel and NSEs, even though steel structures have become the dominant structural form used in modern NZ multistorey construction.

Contracts: Every organization has its own contract requirements, forms, and expectations (some of which are written). This creates a large amount of work. Also, since funds need to be sent overseas, and smooth systems have not been established for this, there is significant iteration, and this takes time. The contract system used for sending funds to China is pay-on-invoice. The contract with Tongji-ILEE is also divided into two phases, which also takes a series of paperwork.

After costing of the different items required for the project was conducted in October 2019, it was found that there was approximately a NZ$64,000 deficit, and this meant that some of the interesting tests need to be eliminated from the test programme. Fortunately, QuakeCoRE provided the opportunity to obtain funds. Of these, about $50k go toward direct experimental costs (and the ROBUST team are very grateful for this). Even then, there is no contingency funding budgeted …. Every expenditure item is requiring sign-off and careful control on costs is key to the project's success.

2 TEST PLAN

The shaking table test plan is shown in Figure 1. Friction devices used include the asymmetric friction connection (AFC), symmetric friction connection (SFC), and the resilient friction connection (RSFJ). These are placed at beam ends, column bases, in braces, and in the tension-only “GripNGrab” device. Structural configurations include, moment frames, braced frames, rocking frames, and rocking columns. The NSEs include different configurations of ceiling, glass curtain wall, internal partition walls (with access holes), precast concrete cladding, and contents. These are subject to unidirectional and bidirectional horizontal shaking. The plan dimensions are 7.25m in the longitudinal direction, and 4.75m in the lateral direction between column centres, and the interstorey height is 3m. Figure 2 shows the test configurations where the symbols have the following meanings: A - AFC, AB – AFC with Belleville springs, BF - base fixed, BP - base pinned, F - fixed, G - gripNgrab, R - RSFJ, RTC - tension-compression RSFJ, RC – rocking column, S - SFC, SB – SFC with Belleville springs, and U - uplift permitted. Some of these are described further below. Table 1 describes the planned test sequence. Further details about the test aims and details are given in MacRae et al. (2019) together with other references.

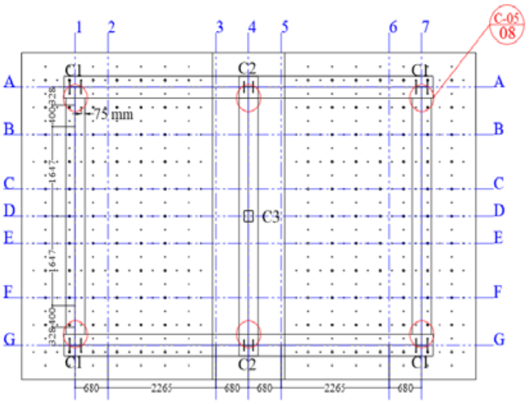
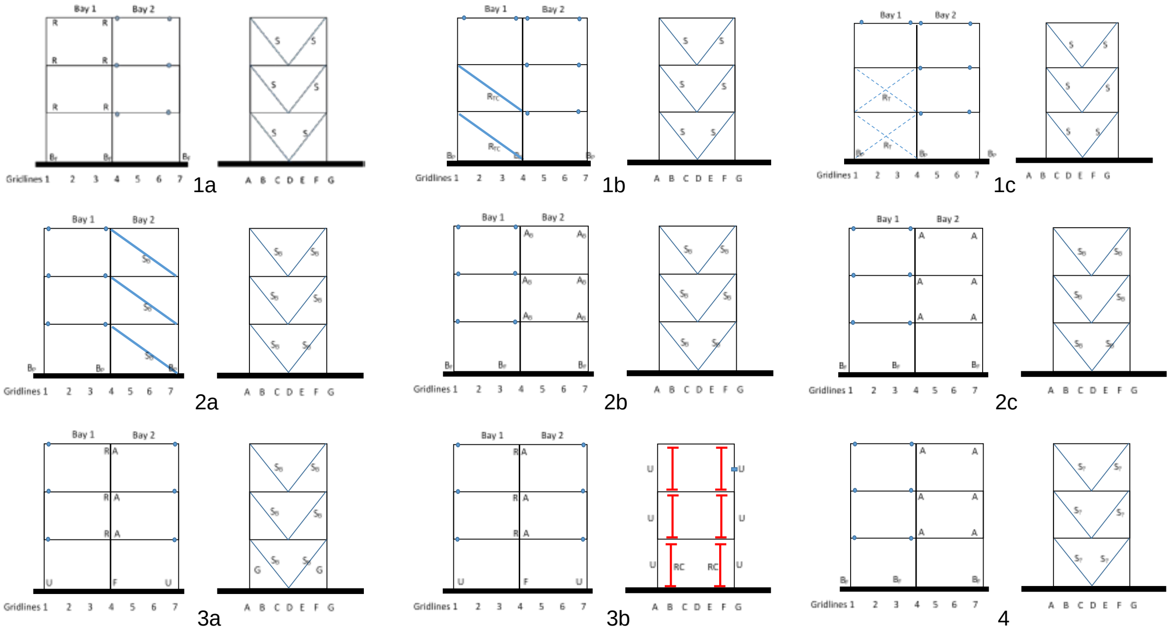


Figure 1. Plan of Test Frame (drawn by Bagheri/Yan)



1a 1b 1c

2a 2b 2c

3a 3b 4

Figure 2. Elevations of the Different Test Configurations (drawn by Yan/Bagheri)

Table 1. Shaking Table Tests (from Yan)

TYPE		**SUBTYPE**	**Longitudinal**		**Transverse**	**NSE**	**Loading Type**
			X		**Y**		
			Bay 1	**Bay 2**	**System**		
1	**RSFJ**	**a**	MRF RSFJ	Pinned	CBF V-braced System-SFC-STD	Basic	X&Bi
		b	BRC CTB RSFJ	Pinned	Same as above	Basic	X&Bi
		c	BRC TOB RSFJ	Pinned	Same as above	Basic	X
2	**AFC&SFC**	**a**	Pinned	CTB SFC-BeS	CBF V-braced System-SFC-BeS	Basic	X
		b	Pinned	MRF SHJAFC_STD	Same as above	Basic	X
		c	Pinned	MRF SHJAFC_BeS	Same as above	Basic	X&Y&Bi
3*	**Rocking System**	**a**	Pinned/RSFJ	SHJAFC/Pinned	RKF GnG	Basic	Y
		b	Pinned/RSFJ	SHJAFC/Pinned	TJ Rocking Column	Basic	Y
4	**NSE**	**-**	Pinned	MRF SHJAFC_BeS	CBF V-braced System-SFC-TBD	Full	X&Y&Bi-Final

In this table the following notation is used: AFC = Asymmetric Friction Connection; Basic = Partition walls and ceilings; BRC = Brace; BSW = With Belleville Washers; CBF= Concentrically Braced Frame; CTB = Brace Effective in Compression and Tension; GnG = GripNGrab; MRF = Moment Resisting Frame; Pinned = Pinned Beam Ends; RSFJ = Resilient Friction Slip Joint; SFC = Symmetric Friction Connection; SHJAFC = Sliding Hinge Joint Asymmetric Friction Connection; STD = Standard with No Belleville Spring Washers; TJ = Tongji; X&Y&Bi = Testing in X, Y and Bi direction; X&Y&Bi-Final = Testing in X, Y and Bi direction up to 2500 year shaking; TOB = Tension Only Brace; X = Longitudinal direction; Y = Transverse direction.

The term “non-skeletal elements (NSEs)” (often referred to as non-structural elements, with the same acronym), was coined by the first author as part of the Tongji University ROBUST research group (22 April 2019) to more accurately define their role as some of these elements having the possibility of contributing to the structural resistance/action. These NSEs include contents, interior partition walls (IPWs) at the ground level, cladding consisting of glazed curtain walls (GCW) at opposite corners, and precast concrete panels (PCP) at the other corners, as well as different configurations of ceiling and piping at the top of the second and third storeys.

The following research questions were some of the considerations used in the above test matrix determination. Some of the questions relate to several of the matrix elements and the performance requirement is related to repair/reinstatement as well. Additional more detailed questions, and comparisons between different systems, are not listed below.

- How do the different RSFJ configurations perform?
- How does column base connection behave under bidirectional loading with (i) braces in both directions, and (ii) a brace in one direction and MRF in the other?
- How does braced SFC frames perform, with and without Belleville springs (BeS)?
- How does MRF SHJ frames perform, with and without Belleville springs (BeS)?
- How does the response of the SHJAFC and RSFJ MRF compare?
- How does the GnG perform?
- How does the rocking column perform?
- How do NSEs behave with large displacements and bidirectional shaking?
- How well does each system self centre at different levels of seismic intensity?
- What is the damage threshold of each system and can repairs be implemented quickly and efficiently as planned?

The timeline as of early January 2020 is as follows (however potentially subject to variation which will be elaborated on at the Conference):

31/1/2020	Completion of final structural design and detailed Design Features Report by students and researchers, to be submitted for external peer review to advisory group/translation partners.
29/2/2020	Completion of external peer review by advisory group. Addressing of all issues arising, and completion of final construction drawings. Start of fabrication.
30/3/2020	Component tests undertaken at Tongji on brace details and rocking column concept
30/4/2020	Completed fabrication of ROBUST frame elements by fabricators, and shipping to Jiading Campus. Initiation of construction outside main lab
31/5/2020	Completion of ROBUST frame construction outside Jiading test lab. Practice of changing configurations starts.
1-3/7/2020	**Workshop on Resilient Steel Buildings** at Tongji University led by MacRae and with many participants. A number of experts from around the world have agreed to come, discuss the ROBUST plan and see the test building. Blind prediction will be made discussed.
1/8/2020	Movement of the structure onto the Tongji Shake table, instrumentation, and initiation of testing
30/9/2020	Completion of all shake table testing, disassembly of the structure and lab clean-up

3 TECHNICAL ISSUES

Many of the technical issues are regarding the structure itself are discussed in accompanying papers by Yan et al. (2020), NSEs by Dhakal et al. (2020), and rocking columns by Jia et al. (2020). Further papers on detailed topics related to the ROBUST programme are also distributed throughout this conference and may be accessed on the OUTPUTS section of the ROBUST Dropbox page (ROBUST, 2018).

It may be seen from the wide variety of issues above, that there are a number of challenges in testing the system. A number of these are listed below:

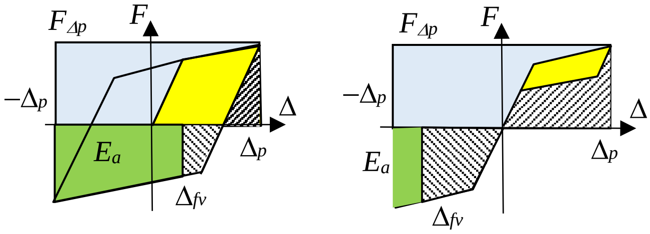
Section availability: Steel sections equivalent to those used in NZ are available in China and are used.

Moving of specimen: Space and time inside the laboratory is expensive, so it is anticipated that the frame will be constructed outside the laboratory and that practice runs changing between different configurations will be undertaken there prior to their being implemented on the shaking table. The completed building is too tall to fit in the laboratory door, so the building will be split into two (with splices at the centre of the middle storey columns), and the frame will be braced, moved into the laboratory, and assembled on the table. A special lifting frame is required to move the frame. The lifting frame has been designed and detailed so it will then provide additional roof mass when it is not fulfilling its lifting role.

Braced frame configuration: Access needs to be provided to the structure so that different elements can be replaced easily without interfering with the slab. This is done by placing the transverse frame braces in a V, rather than inverted V, configuration, with a shear key at the base to carry lateral force to the foundation. This also works well for the installation of the GripNGrab device for the rocking frame of Configuration 3a. For realistic buildings, the inverted V shape is preferable as it provides more natural lateral stability to the rocking frame. This was a compromise of the project.

Rocking frame displacement prediction: The SCNZ method (Wiebe et al. 2015) for predicting the response of the rocking frame multiplied the displacements obtained using standard NZS1170.5 methods by 1.3 (Gledhill, 2015). This is similar to the approach in FEMA356 documents where a multiplier, C_2, is used on the elastic displacement to estimate peak displacement in the cases with pinched hysteresis loops. Such an approach is problematic in general because, even if there is no rocking frame uplift or yielding, it indicates that the peak displacements, Δ_p, should be 1.3 times greater than the elastic displacement, Δ_e, when it is obvious that it should be the elastic displacement in this case. An alternative has been proposed by Penucci et al. (2011), giving $\Delta_p = R^{0.3}\Delta_e$, however, this is also problematic as it does not consider the effect of structural period on the increase in structural response. Instead, it is considered that using $\Delta_p = (\mu^{\alpha}/R).\Delta_e$, where μ is the structural ductility obtained using standard code methods (e.g. NZS1170.5) where α is dependent on the hysteresis loop shape, may be a better parameter as proposed by MacRae (2017). Here, α required validation from numerical analyses and experimental testing.

Initial studies by Rangwani et al. (2020) indicate that inelastic displacement prediction may be less than 25% of the actual inelastic demand from time history analysis for this short period structure, with a very pinched hysteresis loop at the design level (500 year) shaking intensity. This is because short period structures may be subject to many more cycles of ground motion than longer period structures, and are therefore more likely to oscillate, especially if their resistance to oscillation is low. The first author has recently proposed an Oscillation Resistance Ratio (*ORR*) which increases for higher peak ductilities and for fatter (i.e. less pinched) hysteresis loops as described in Soleimankhani et al. (2020). The *ORR* may be defined as (i) the energy remaining for an oscillator to move to a greater displacement in the opposite direction than in the initial direction (shown as the green area E_a in the Figure 3), divided by (ii) two times the strength at peak displacement, $F_{\Delta p}$, multiplied by the peak displacement of the structure, Δ_p, shown by the light blue rectangle. That is, $ORR = E_a/(2F_{\Delta p}\Delta_p)$. The term $2F_{\Delta p}\Delta$ is simply a convenient normalization resulting in *ORR* normally ranging between zero and unity for loops without degradation. Here, if a structure reaches the displacement at the upper right part of the hysteresis loop, and then oscillates in free vibration (ignoring damping) then it will release potential energy and use that energy again as it moves in the opposite direction, so the shaded areas are equal. It moves to the displacement associated with free vibration, Δ_{fv}, which is less than Δ_p in the cases shown. For the oscillator to oscillate further in the reverse direction, it needs to have the energy E_a input into the system. Here, it may be seen that the bilinear loop requires substantially more energy (i.e. E_a) to cause oscillation in the reverse direction than does the flag-shaped loop. Therefore, oscillation is less likely, and the likelihood of increased displacements is reduced. A symmetric elastically responding structure has $ORR = 0$.



(a) Bilinear loop
High ORR

(b) Flag-Shaped Loop
Low ORR

Figure 3. ORR for Different Hysteresis Loops

Using ORR, many aspects of inelastic structural response may be explained. For example,

a) Different design approaches and period dependence of response. It is difficult for long period structures with a high ORR during a typical far field earthquake record to reach large displacements more than once as it has one significant inelastic excursion, so the displacement is controlled by the loading characteristics of the curve and is independent of the unloading characteristics. This is consistent with the equal displacement assumption used for a range of structures in most design standards. However, for structures with a low *ORR* (e.g. pinched loops) subject to several cycles of reverse loading (due to the record being of long duration, or the structure being of short period and subject to a number of cycles), the structure is likely to have greater demands in the reverse direction, and the peak displacement response is likely to be dependent on the unloading characteristics of the hysteresis curve. This is consistent with the substitute structure concept popularised by Gulkan and Sozen (1974) and later developed further by Priestley et al. (2007). It is anticipated that α value above may also be dependent on the *ORR*. For our case, $\alpha = 2.06$.

b) Different types of motion. For high *ORR* structures (e.g. typical steel or concrete structures) with a fundamental period of about 1s subject to *ground motions with a high pulse content* (such as some near fault records), yielding structures are unlikely to oscillate in the reverse direction. However, the so-called “high inelastic demand, Δ_i” of such oscillators may perhaps be better termed “low elastic

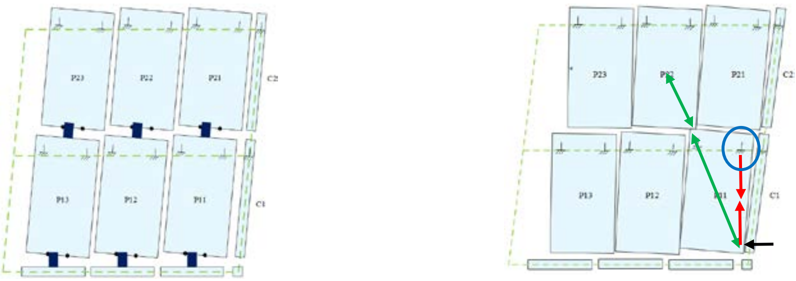
> demand, Δ_e" because the record duration is not long enough to cause the elastic structure to significantly oscillate, even though the elastic structure *ORR* is low. This is consistent with the concept of the equal energy method to estimate peak displacement response under impulse excitation. That is Δ_i/Δ_e is high because Δ_e is low. For, *ground motions with long duration of long period shaking,* such as the 1985 Mexico City SCT1 record, the yielding structure is caused to oscillate giving an inelastic demand that may be higher than the elastic demand (even though the elastic structure may also oscillate somewhat). That is Δ_i/Δ_e is high because Δ_i is high. For *normal far-field moderate duration ground motions,* the equal displacement concept is often considered to hold (i.e. $\Delta_i \approx \Delta_e$). Here the yielding structure may not reach a high displacement more than once because the ORR is high, whereas the elastic oscillator oscillates several times (since ORR is low) resulting in significantly larger elastic displacements than that estimated by the equal energy method. That is $\Delta_i/\Delta_e \approx 1.0$ because the elastic oscillator oscillates, while the inelastic one does not. Structures subject to the highest Δ_i/Δ_e are therefore expected to be those with low ORR subject to many cycles of loading, as is the case with our short period rocking frames.

Rocking column concept: This concept is originated from seismic mechanisms of Chinese ancient wooden pagodas, and proposed by the Tongji team. In fact, the seismic mechanisms of Chinese wooden pagodas are far more complicated and fascinating. This uses the vertical load on the columns multiplied by the eccentricity of the rigid column pedestal to provide a restoring force. The higher the vertical load, the greater the restoring force, however too high a vertical load can lead to local column yielding. There was a reluctance to provide post-tensioning on the rocking configurations of 3a and 3b, especially as the rocking frame of configuration 3a would recentre without much restoring force since the GripNGrab device does not resist compression. As a result, the rocking frames in the transverse directions in configurations 3a and 3b have not been separated from the structure, as is generally desirable. Instead, they have been placed under the floor slab, and the floor slab bends and resists the frame uplift. It is expected, using a similar approach to that of Clifton and Momtahan (2014), that the slab will remain elastic under the expected design level actions.

Column twisting: In order to access the connections to allow building elements to be changed in the different configurations, the slab is significantly separated from the building columns. As a result of the connections on the column sides often having little restraint against beam lateral movement, there is low torsional restraint provided to the columns. There was concern that this may result in early failure. To mitigate this possibility, beam continuity plates at the central edge column in the longitudinal frame were extended and bolted to the gravity beam top flange with 4 bolts. At the corner columns, transverse direction beams were desired to have no moment in the in-plane direction so these connections could be modelled as perfect pins. This effect was achieved by a flexible beam end-plate connection to the column web with the 4 end-plate bolts placed inside the beam flanges. Lateral restraint at the transverse beam end, restraining the column against twist, was achieved by (i) placing the brace connection extension below the beam inside the column flanges, so the column flanges would restrain out-of-plane movement, and (ii) extending the horizontal column stiffener plate between the column flanges and above the beam top flange, and placing vertical dowels/bolts through this to resist beam top flange movement too.

Access windows: In order to inspect the "low damage structure" to see whether is damaged or not (without damaging it!), special access/inspection windows are placed within the IPWs. This is a simple, important, and novel feature of the project which has been part of the concept from the very beginning in 2016. As well as inspection, replacement of bolt and shims allowing complete joint reinstatement, is possible.

Vertical non-skeletal elements (NSE): Internal partition walls (IPW), glazed curtain walls (GCW) and precast concrete panels (PCP) are generally designed to deform by rocking, as shown in Figure 4a. Shear keys allow the rocking thus avoiding panel clashes. Furthermore, a typical Chinese GCW without shear keys is proposed by the Tongji group because this represents current Chinese construction. In fact, some conventional GCW details also have shear keys, while the gaps are fairly large, which is employed to resist the wind load at large displacement. The drift capacity of this before the bottom panel starts to lift the panel above (as shown in Figure 4b) is related to the vertical and horizontal gaps beside the corner panels. Even after contact is made, it does not necessarily cause failure. Instead, the weight of upper storey inner panels may be carried by the lower panel. The lower panel and its supports (e.g. that shown by the blue circle) must be strong enough to resist this. Such a mechanism, which may be appropriate for shorter buildings, is being studied. Because these vertical NSE used here are designed to not have significant damage, and to not resist significant structural forces, frame displacements may be larger than in conventional systems where NSE provide stiffness and strength to the systems. This relative increase in displacement needs to be acknowledged in design.



(a) Rocking Mode (with shear keys) (b) Typical Chinese Construction (without shear keys)

Figure 4. GCW Deformation Modes (Courtesy Can Chen)

Instrumentation: The laboratory instrumentation system can manage 220 channels of data at 200Hz. Other systems are required for more data. It is anticipated that in addition to the laboratory system, high speed high definition black and white cameras will be used to record displacement information. This is being conducted in collaboration with Tongji measurements group and will be useful for the data management. Through cooperation with multidiscipline researchers, a lot of difficulties can be solved more effectively. Measurements of the rocking column system and NSEs with rocking details are more straightforward by using the high speed camera system.

Shaking table capacity: The frame is large, so it will be placed on top of two shaking tables (B and C) in the Jiading campus of Tongji University. These are required to move together and the structure sits on a robust foundation ring beam to lock the response of the two tables together and mitigate any slight variation in response of the individual tables. The Jiading combined shaking table capacity seems to be controlled by the overturning moment, but there has been significant variation in the behaviour in the past, so accurate calculations are not useful. The capacity provided is about is 8000kNm. It is measured by sensors below the table which will cause shutdown if demands are too large. Impact and other effects may influence the shutdown. Discussions with the laboratory manager indicate that the demand may be reached for our 3 storey frame, with a PGA input of about 0.60g, but weakening the structure may allow greater inputs. In addition, experiences and lessons of the previous Tongji-NZ ILEE concrete project provides a lot of helpful information for us.

Record Selection: One two-directional horizontal earthquake recording is used for all runs due to time resource limitations. The selection process is as follows. From the two horizontal components of a number of ground motion records, analyses are performed with each record in different orientations to find the orientation with the largest response for the fundamental period corresponding to the most flexible ROBUST configuration. This then becomes the main earthquake shaking direction for that record. The record with the best fit to the code spectra over the range of ROBUST configuration fundamental periods is then selected as the record for use. Using this process, when the record is applied at any angle to the building axis, the shaking return period is about the same. Analyses using the record are applied in each direction separately, and at 45 degrees, with and without the perpendicular component. Both actual and artificial records were considered.

Rocking frame shaking directionality: Since the rocking frame causes uplift of the exterior columns on one longitudinal frame only, this makes the building irregular in the other direction. This would cause building plan torsion when shaking is applied in the longitudinal direction. This is undesirable, and it is not an effect that was wanted to be investigated, so shaking will only be applied in one direction at a time for this configuration. This means that 2-directional horizontal shaking will not be applied to this rocking configurations in 3a of Table 1. This was a compromise of the project. In real structures an external rocking frame solves this issue.

Repair decision matrix: Repair decisions, involving retightening bolts, or replacement of bolts and shims, are required. A decision matrix has been developed as a function of the sliding distance. For properly installed Belleville springs, it is likely that no reinstatement of the bolts may be required before the bolts reach the end of the holes.

4 CONCLUSIONS

This paper describes some aspects of the ROBUST Project collaboration. It is shown that:

1) Collaboration brings its own opportunities and challenges. Many new things can be done and significant benefits obtained in a collaborative environment, but care is needed to successfully navigate and realize such benefits given different cultures, languages and institutional policies. Resources to help with this are helpful. It is believed that developing trust is key to smooth relationships. It is believed that the ROBUST team members are fortunate to have good people to work with.
2) The ROBUST test involves the shaking table testing of a full scale 3 storey building with a steel frame and cold formed steel-concrete composite deck on the Jiading Campus shaking table at Tongji University, Shanghai, China. Energy is dissipated by means of different types of friction connections in frames with different structural configurations. The building includes typical NSEs detailed for low damage.
3) A number of technical issues were discussed including frame, NSEs, instrumentation, and application of shaking, and repair. Many of these are new, or unique to, this testing.

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