Final report on the EQC project 14/U687 - (3708078)

Sliding Hinge Joint Connection with Belleville Springs

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May 2018 - The University of Auckland (UoA)

Research outcomes:

The key steps in this PhD research undertaken since 1/9/2013 are described below.

This research topic is a landmark one for New Zealand and has made us the acknowledged world leading country (by Italian, Canadian, USA and Taiwanese researchers in this field) in friction sliding seismic connections research. The concept with the Sliding Hinge Joint is that it is; 1) rigid under normal conditions, 2) allows rotation of the columns relative to the beams through controlled friction sliding in a severe earthquake, 3) then seizes up and returns to its pre-earthquake position, stiffness and sliding threshold at the end the earthquake.

The research started in 1998 and the SHJ as currently implemented in practice achieves the first two of these three key criteria, but does not achieve the third to a satisfactory extent. Nevertheless, even in its current form it is one of the best performing low damage seismic resisting systems developed and is now used on over NZD 4 billion of new buildings, some of which have been through up to two severe earthquakes (August 2013 Grassmere and November 2016 Kaikoura) with no damage.

This research has focussed on achieving the third criterion, which is significantly the most difficult to achieve, with a solution that will also enhance the tendency of the SHJ to return to its pre-earthquake position, thus self centering the building.

This research includes all of the required experimental works which have been kindly funded by the EQC. Currently, the analytical and numerical work is being finalized and more journal articles and reports are being written, this includes the PhD thesis which will be defended in May 2018. The EQC support will be proudly acknowledged in all of the upcoming papers/presentations. The experimental research includes using the customized tools that have been discussed with different suppliers from NZ, Canada, and USA to fit for purpose.

1. Proposing an analytical stiffness based approach to design and use Belleville springs (BeSs) in the sliding hinge joint (SHJ) (applicable to all of the friction seismic energy dissipators) based on mathematics' and solid mechanics' first principles. This research is completed and has been to show how friction slider behaves, how a Belleville spring behaves in the SHJ and can be used to:

1) Minimize post-earthquake clamping force loss

2) Minimize unwanted prying effects

3) Improve the self-centring capability of the joint

4) Increase the system coefficient of friction

5) Increase the consistency of the joint behaviour

6) Decrease the degradation of the sliding surfaces

7) Increase the consistency of the achieved installed bolt tension using a proposed turn of the nut method

2. Proposing a methodology to inspect, prepare, and install the high strength bolts to increase the delivered clamping force. This was following finding out a significant issue with the HSFG bolts, and based on analytical and experimental research led to proposing changes on the current bolting practice in New Zealand. The required recommendations have also been reported to SCNZ and delivered to the MBIE. A bolt tightening test setup was designed to carry out the experiments related to bolting. This work is completed and has been incorporated into two standards as noted below.
3. Proposing a turn-of-the-nut method of tightening the SHJ bolts within their elastic range with using Belleville Springs, to provide an accurate measure of the installed tension. This work, which is completed, is based on analytical and experimental research on the bolt tightening test setup looking at the following parameters:

   1) Applied torque on the nut measured by a customized smart socket

   2) Deflection of the Belleville springs by a customized digital height gauge

   3) Rotation of the nut

4. Undertaking 9 AFSHJ experiments with different configurations of Belleville springs and with no Belleville springs to determine the effects of the BeSs on the SHJ seismic behaviour. This was performed using the previously established custom made SHJ test rig. In these tests, all influential parameters were measured and the test results confirmed the benefits of the proposed approach of using Belleville springs. This work is completed.
5. Designing/Developing an AFC test setup to be used on the MTS machine and undertaking 27 AFC tests (now completed) to Investigate the following subjects:

   1) Effects of the surface roughness, on the joint sliding behaviour to determine the optimum surface preparation level for the joint's plies.

   2) The possibility of using the Sliding Hinge Joint not only in dry internal environments as is recommended currently. This included testing the rusted plies.

3) Benefit of using Titanium Nitride coated shims.

4) The behaviour of a shim-less Sliding Hinge Joint with an abrasion resistant cleat.

5) The behaviour of the Sliding Hinge Joint with abrasion resistant cleat and shims.

6. Undertaking 9 AFC component tests on the MTS machine and establishing the optimum level of the elastic installed bolt tension. This is completed. A paper was presented on this at the 2017 NZSEE conference.
7. Undertaking an AFC component test on the MTS machine using customized Belleville springs to confirm the ability of the BeSs to maintain most of the bolt tension after two severe earthquake loading regimes. This is completed and formed part of the 2017 NZSEE conference presentation.
8. Developing an analytical approach to design and use linear springs such as Lurethane spring to make the friction dampers statically self-centre. This is completed.
9. Finite element modelling of the Asymmetric Friction Connection with and without BeSs using ABAQUS FEA to investigate various parameters such as the out of plane flexibility of the beam flange. This is underway.
10. Developing a SDOF and MDOF systems to numerically and dynamically research the SHJ self-centring capability in component level as well as in a building using SAP2000 based on direct integration NLTH analysis. The SDOF part is completed on which a paper was presented at the 2017 NZSEE conference. The MDOF part is under the development and will be completed in 2018.
11. Developing mathematical modelling for the SHJ and AFC to optimize the joint's design and behaviour, for example regarding the beam to column gap and generated prying forces. (under development)
12. Theoretically deriving the moment-rotation hysteresis of the SHJ from the first principles. (under development, and very close to be finalized)
13. Developing an elastic mathematical bolt model for the AFC design. This will also make it possible to calculate the installed bolt tension to prevent the bolts' material to yield. (under development, and very close to be finalized)
14. Developing a mathematical bolt model for the bolt tightening to set a torque threshold with respect to the clamping force to prevent yielding the bolt material in torsion.(under development)

STANDARDS (CODE) CONTRIBUTION:

Proposed additions and changes to Australia and New Zealand Steel Structures Standards (NZS3404, AS/NZS1252: 2016, and AS/NZS 5131: 2017). They have been implemented in the latter two editions.

Publications and presentations on the SHJ PhD research:

Link to download the publications:

https://www.researchgate.net/profile/Shahab_Ramhormozian

Journal papers:

- *Shahab Ramhormozian, G. Charles Clifton, Gregory A. MacRae, George P. Davet, Stiffness-Based Approach for Belleville Springs use in Friction Sliding Structural Connections, Journal of Constructional Steel Research (JCSR) 138 (2017): 340-356.*
- *Khoo, Hsen-Han, Charles Clifton, Gregory MacRae, Hao Zhou, and Shahab Ramhormozian. "Proposed design models for the asymmetric friction connection." Earthquake Engineering & Structural Dynamics 44, no. 8 (2015): 1309-1324.*
- *Shahab Ramhormozian, G. Charles Clifton, Gregory A. MacRae, Hsen Han Khoo , The Sliding Hinge Joint: Final Steps towards an Optimum Low Damage Seismic-Resistant Steel System, Key Engineering Materials, Vol. 763, pp. 751-760, 2018*

Conference papers:

- *Ramhormozian S., Clifton G.C., MacRae G.A.. (2014). The Asymmetric Friction Connection with Belleville Springs in the Sliding Hinge Joint. Proceedings of the New Zealand Society for Earthquake Engineering Annual Conference 2014, Auckland, New Zealand, March 21–23, 2014.*
- *Ramhormozian, S., Clifton, G. C., Nguyen, H., (2015). Determination of the Required Part-turn of the Nut with Respect to the Number of Free Threads at Loaded Face of the Fully Tensioned High Strength Friction Grip Property Class 8.8 Bolts. Steel Innovations Conference, Auckland, New Zealand.*
- *Ramhormozian S., Clifton G.C., MacRae G.A., Khoo H.H.. (2015). The High Strength Friction Grip Property Class 8.8 Bolts: Variability of Installed Tension and Potential Resulting Effects on the Friction-type Connections' Behaviour. New Zealand Society for Earthquake Engineering Annual Conference 2015, Rotorua, New Zealand, April 10–12, 2015.*
- *Ramhormozian S., Clifton G.C., MacRae G.A., Khoo H.H.. The Optimum use of Belleville Springs in the Asymmetric Friction Connection, (2015) The 8th STESSA Conference on Behaviour of Steel Structures in Seismic Areas, Shanghai, China.*
- *Ramhormozian S., Clifton G.C., MacRae G.A., Khoo H.H.. Improving the Seismic Behaviour of the Sliding Hinge Joint using Belleville Springs, (2015) The 8th STESSA Conference on Behaviour of Steel Structures in Seismic Areas, Shanghai, China.*
- *Ramhormozian, S., G. C. Clifton, D. Cvitanich, S. Maetzig and G. A. Macrae (2016). Recent Developments on the Sliding Hinge Joint. The 2016 New Zealand Society for Earthquake Engineering (NZSEE) Annual Technical Conference - Reducing Risk Raising Resilience. Christchurch, New Zealand*

- *Ramhormozian, S., G. C. Clifton, D. Cvitanich, S. Maetzig and G. A. Macrae (2016). Influence of the Asymmetric Friction Connection (AFC) ply configuration, surface condition, and material on the AFC sliding behaviour. The 2016 New Zealand Society for Earthquake Engineering (NZSEE) Annual Technical Conference - Reducing Risk Raising Resilience. Christchurch, New Zealand*
- *Ramhormozian, S., G. C. Clifton, K. Cowie (2016). Proposed Changes on NZS 3404 Specified Part-turn Method of Tensioning High Strength Friction Grip (HSFG) Property Class 8.8 Bolts. The 2016 New Zealand Society for Earthquake Engineering (NZSEE) Annual Technical Conference - Reducing Risk Raising Resilience. Christchurch, New Zealand*
- *Shahab Ramhormozian, George Charles Clifton, Yoshie Takayama, Julie Lam, Gregory A. MacRae, Self-Centring Capability of the Seismic Friction Dampers: A Conceptual Study on the Static and Dynamic Self-Centring Requirements for the Single Degree of Freedom (SDOF) Asymmetric and Symmetric Friction Connections (AFC and SFC), The 2017 New Zealand Society for Earthquake Engineering (NZSEE) Annual Technical Conference. Wellington, New Zealand.*
- *Shahab Ramhormozian, George Charles Clifton, Brent van Bergen, Marty White, Gregory A. MacRae, An Experimental Study on the Asymmetric Friction Connection (AFC) Optimum Installed Bolt Tension, The 2017 New Zealand Society for Earthquake Engineering (NZSEE) Annual Technical Conference. Wellington, New Zealand.*
- *Shahab Ramhormozian, Shannon Abeling, Mehdi Sarrafzadeh, Harold Aquino, George Charles Clifton, The 2016 IDEERS Seismic Design World Conference and Competition: A Report by New Zealand Postgraduate Team from the University of Auckland (UoA), The 2017 New Zealand Society for Earthquake Engineering (NZSEE) Annual Technical Conference. Wellington, New Zealand.*
- *Shahab Ramhormozian, George Charles Clifton, Sian English, Samantha Fredheim, Sherif Beskhyroun, Gregory A. MacRae, Dynamic Performance Analysis and System Identification (SI) of a Low Damage Multi-Storey Structural Steel Building under two Moderately Severe Earthquake Events using Structural Health Monitoring (SHM) Data, The 2018 New Zealand Society for Earthquake Engineering (NZSEE) Annual Technical Conference. Auckland, New Zealand.*
- *Ramhormozian S., Clifton G.C., MacRae G.A., Khoo H.H.. The Sliding Hinge Joint: Final Steps towards an Optimum Low Damage Seismic-Resistant Steel System, (2018) The 9th STESSA Conference on Behaviour of Steel Structures in Seismic Areas, Christchurch, New Zealand.*

Reports:

Ramhormozian, S., G. C. Clifton, K. Cowie and H. Nguyen (2015). Determination of the Required Part-turn of the Nut with Respect to the Number of Free Threads Under the

Loaded Face of the Nut in Fully Tensioned High Strength Friction Grip Property Class 8.8 Bolts. Steel Construction New Zealand (SCNZ), University of Auckland (UoA).

Workshop papers:

- *Ramhormozian, S., G. C. Clifton, (2016). Enhancing the Seismic Performance of the Sliding Hinge Joint Using Belleville Springs. The 2016 DPRI-QuakeCoRE Student Forum - 26-27 February. Kyoto, Japan.*

Journal papers (in preparation) based on the currently available materials or ongoing research:

- 9 Journal papers have been discussed with Associate Professors Charles Clifton and Greg MacRae, have been written and reviewed or are to be finalized in 2018/19 on the analytical, numerical, and experimental aspects of the research.

PRESENTATIONS AND LECTURES BY INVITATION

- *Ramhormozian Shahab, Djojo Gary, Clifton Charles,* Low damage steel seismic resisting systems*, 2014 Earthquake Engineering Research Symposium, The University of Auckland Centre for Earthquake Engineering Research (UACEER). Presented by Shahab*
- *Presenting oral and poster papers at the following conferences and workshops:*
  - *2014, 2015, 2016, 2017, and 2018 NZSEE conferences in New Zealand (6 posters and 3 orals)*
  - *2015 Steel Innovations Conference, Auckland, New Zealand (1 oral)*
  - *The 8th STESSA Conference on Behaviour of Steel Structures in Seismic Areas, 2015, Shanghai, China. (2 orals)*
  - *The 9th STESSA Conference on Behaviour of Steel Structures in Seismic Areas, 2018, Christchurch, New Zealand. (1 oral)*
- *The 2016 DPRI-QuakeCoRE Student Forum - 26-27 February. Kyoto, Japan (1 oral) – **By Invitation***
- *The 2016 and 2017 QuakeCoRE annual meeting, Taupo, New Zealand (4 Posters)*
- *The 2016 IDEERS earthquake Eng. Conference/competition. Taipei, Taiwan (1oral)*
- *Lecture on the SHJ at the University of Salerno, Italy (2017) (1 oral)- **By invitation***
- *Lecture on the SHJ at the University of Coimbra, Portugal (2017) (1 oral)- **By invitation***