A robust procedure for analysis and design of seismic resistant structures with flag-shaped hysteretic damping systems

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Introduction

Different design codes around the world have different approaches to determine the design seismic loads yet most of them recommend reducing the elastic base shear by a factor that is related to the ductility of the structure. While the flag-shaped energy dissipation devices bring superior seismic performance (including the self-centring behaviour) for the structure, lack of a robust and efficient method for designing and sizing these dampers may be a barrier for the decision-makers to adopt this technology. One important reason could be the extra cost resulted from the inefficient sizing of the structure and the devices.

This study provides a robust step-by-step analysis and design procedure for engineers in practice and researchers for designing a structure with flag-shaped damping systems. This procedure which is based on the Equivalent Static Method (ESM) may require pushover and nonlinear time-history analyses to verify the performance.

Resilient Slip Friction Joint (RSFJ)

Figure 1 shows the components and the assembly of the RSFJ. In this joint, energy is dissipated by the frictional sliding of the middle moving plates while the specific shape of the ridges combined with the use of disc springs provide the necessary self-centring behaviour. Figure 1(c) shows the device at rest when the disc springs are partially compacted. When the force applied to the joint overcomes the resistance between the clamped plates, the middle plates start to move, and the cap plates start to expand until the joint reaches the maximum deflection where the disc springs are flattened (see Figure 1(d)).

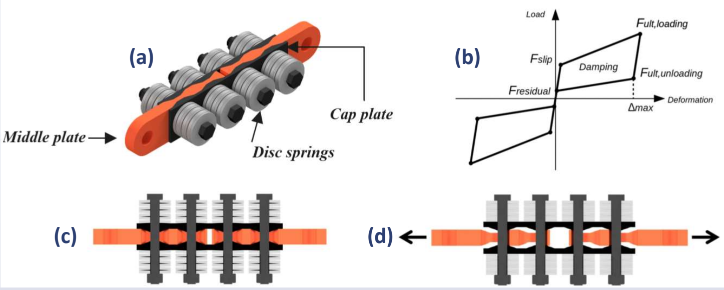


Figure 1. The Resilient Slip Friction Joint (RSFJ)*

The analysis and design procedure

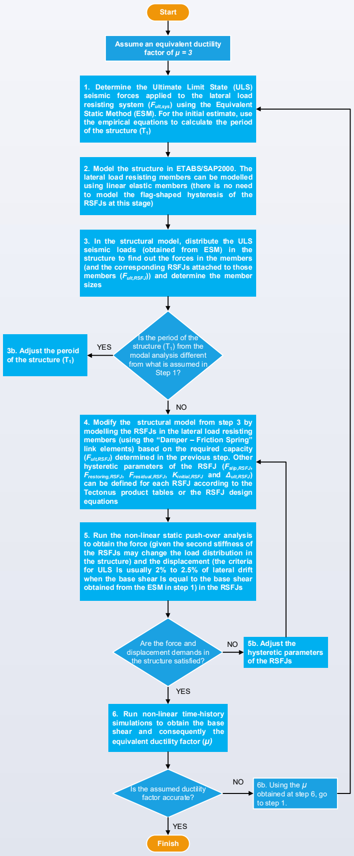
Damage avoidance self-centring systems are usually more sophisticated in design and also pricier compared to the conventional low damage systems that rely on yielding of the designated components to resist earthquakes. Furthermore, RSFJ is also is quite flexible in terms of the wide range of specifications (target force and displacement) it can offer. Therefore, the need for a robust method or a procedure available for the designers so that they can optimise the specifications of the RSFJs and size the devices is critical.

Accordingly, the step-by-step structural analysis and design procedure shown in Figure 2 is developed and recommended to be used when designing with RSFJs. The overall aim of the procedure is to follow the "equivalent ductility" approach and determine the optimum force/displacement capacity of the RSFJs based on a given structural performance and accordingly size the devices.

Design example

A design example case study building is considered to follow the proposed procedure. The building is a five-story structure that uses Cross Laminated Timber (CLT) floors, CLT load-bearing walls as the gravity loads resisting members and balloon type CLT shear walls with RSFJ hold-downs at the bottom corners as the lateral load resisting system. It was assumed that the floors and the CLT walls are 200 mm thick panels with five layers of MSG8 timber. The load-bearing CLT panels were assumed to be 150 mm thick with three layers.

** A Resilient Slip Friction Joint, Patent No. WO2016185432A1, NZ IP Office, 2015.*


Start

Assume an equivalent ductility factor of $\mu = 3$

1. Determine the Ultimate Limit State (ULS) seismic forces applied to the lateral load resisting system ($F_{ult,sys}$) using the Equivalent Static Method (ESM). For the initial estimate, use the empirical equations to calculate the period of the structure (T_1)

2. Model the structure in ETABS/SAP2000. The lateral load resisting members can be modelled using linear elastic members (there is no need to model the flag-shaped hysteresis of the RSFJs at this stage)

3. In the structural model, distribute the ULS seismic loads (obtained from ESM) in the structure to find out the forces in the members (and the corresponding RSFJs attached to those members ($F_{ult,RSFJ}$)) and determine the member sizes

Is the period of the structure (T_1) from the modal analysis different from what is assumed in Step 1?

YES

3b. Adjust the peroid of the structure (T_1)

NO

4. Modify the structural model from step 3 by modelling the RSFJs in the lateral load resisting members (using the "Damper – Friction Spring" link elements) based on the required capacity ($F_{ult,RSFJ}$) determined in the previous step. Other hysteretic parameters of the RSFJ ($F_{slip,RSFJ}$, $F_{restoring,RSFJ}$, $F_{residual,RSFJ}$, $K_{initial,RSFJ}$ and $\Delta_{ult,RSFJ}$) can be defined for each RSFJ according to the Tectonus product tables or the RSFJ design equations

5. Run the non-linear static push-over analysis to obtain the force (given the second stiffness of the RSFJs may change the load distribution in the structure) and the displacement (the criteria for ULS Is usually 2% to 2.5% of lateral drift when the base shear Is equal to the base shear obtained from the ESM in step 1) in the RSFJs

Are the force and displacement demands in the structure satisfied?

NO

5b. Adjust the hysteretic parameters of the RSFJs

YES

6. Run non-linear time-history simulations to obtain the base shear and consequently the equivalent ductility factor (μ)

Is the assumed ductility factor accurate?

NO

6b. Using the μ obtained at step 6, go to step 1.

YES

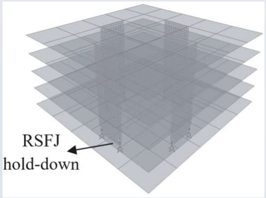
Finish

Figure 2. The recommended analysis and design procedure

The building was designed for soil type C in Christchurch, New Zealand. The total height of the structure is 15 m with 5 m wide spans. Figure 3 shows the typical plan view of the structure where each wall uses two RSFJs at the base level. The design permanent loads were specified as 3 kPa and 1.6 kPa for the first four floors and the roof, respectively. The design imposed loads were assumed 2.0 kPa and 0.5 kPa for the first four floors and the roof, respectively. the lateral drift ratio was kept under 1.5%.

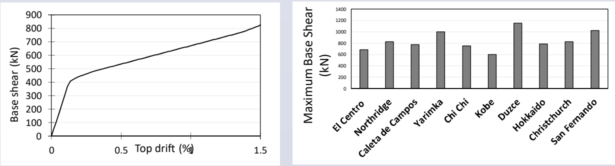
The numerical are displayed in Figure 4. The structure is pushed to 1.5% of lateral drift corresponding to 225 mm of deflection at the roof. Please note that the terminology "non-linear static pushover analysis" is used here but the non-linearity is in fact provided by the non-linear geometrical behaviour of the RSFJs. All structural components up to the design drift (1.5%) still behave within their elastic limit.

Figure 3. Case study structure



the new equivalent ductility factor is back calculated as μ = 3.4. (Note that the period of the structure is less than 0.7 seconds) and the k_{μ} derived from the records. Given that this ductility factor is higher than the first assumption in Step 1 (μ = 3.0), the procedure needs to be repeated from the start with the new equivalent ductility factor of μ = 3.4.

Figure 4. Numerical results



When using the displacement-based design method to analyze and design structures with this system, it is recommended to verify the hysteretic damping ratio assumed for the structure using the results of the nonlinear cyclic pushover analysis (Figure 5) and the equation below. The hysteretic damping ratio for this structure is accordingly determined as 9.5%.

$$\xi_{hyst} = \frac{2\,A_1}{\pi\,A_2}$$

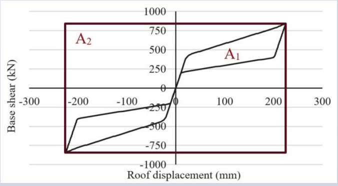


Figure 5. The system hysteretic damping ratio resulted from cyclic pushover analysis

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