Seismic Rehabilitation of Deficient Steel Braced Frames with Conventional and Innovative Retrofit Techniques

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1. Objectives

- **Investigate the seismic behavior of a steel Concentrically Braced Frame (CBF) using Non-Linear Static Analysis and the Performance-Based Earthquake Engineering**
  - Model the structure with the concentrated plasticity approach
  - Highlight the structure main deficiencies
  - Compare them to the actual damages of the structure after the 2011 Tohoku-Oki Earthquake
- **Propose seismic retrofit solutions**
  - *Based on the Capacity Design*: New Chevron braces; New X-braces
  - *High-performance system*: Rocking Braced Frame
- **Compare the performance of the retrofit solutions**

2. Steel CBF structure

- **Two-story Parking Garage with CBF structure**
  - Columns: HSS 200x200x9, S235
  - Beams:
    - *E-W direction*: H-350x180x7x11, S235
    - *N-S direction*: H-450x200x9x14, S235
  - Braces: O-165x6, S275
  - Single-lap gusset plates, creating a 12-mm eccentric load transfer to the braces
  - CBF span length:
    - *E-W direction*: 4500 mm
    - *N-S direction*: 7500 mm
- **Location**
  - Oroshimachi District, Sendai (Japan)

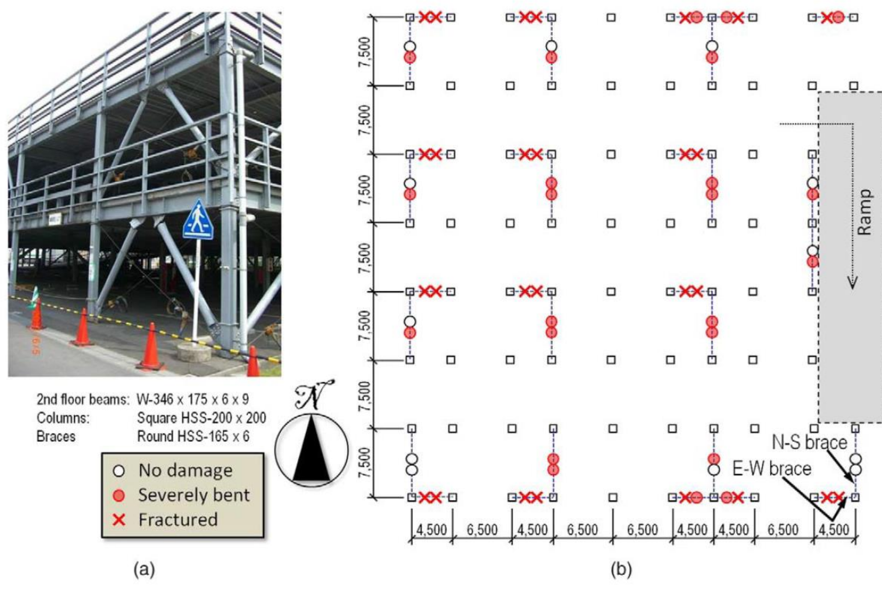


Fig. 1: Parking Garage: (a) Photo; (b) Floor plan

3. Earthquake

- **The structure suffered the 2011 Tohoku-Oki Earthquake**
  - Magnitude M_w 9.0, 200 seconds long
  - Recorded by station MYG013 of NIED and station N°23 of DCRC within the Oroshimachi District
- **Observed Deficiencies after the event**
  - Most of the 1st story gusset plates fractured in the E-W direction and were severely bent in the N-S direction
  - Plastic Hinge appeared in the beam due to the unbalanced load from the braces
  - Residual drift: 1% in the E-W direction; negligible in the N-S direction

Fig. 2: Fractured Gusset Plates

Fig. 3: Beam deformation

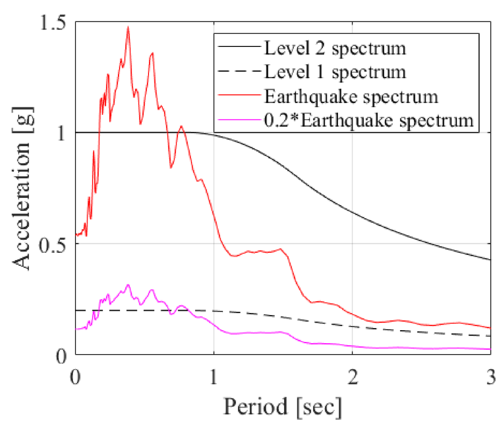


Fig. 4: Spectrum

4. Numerical Model

- **Non-linear model in OpenSees, using the concentrated plasticity approach**

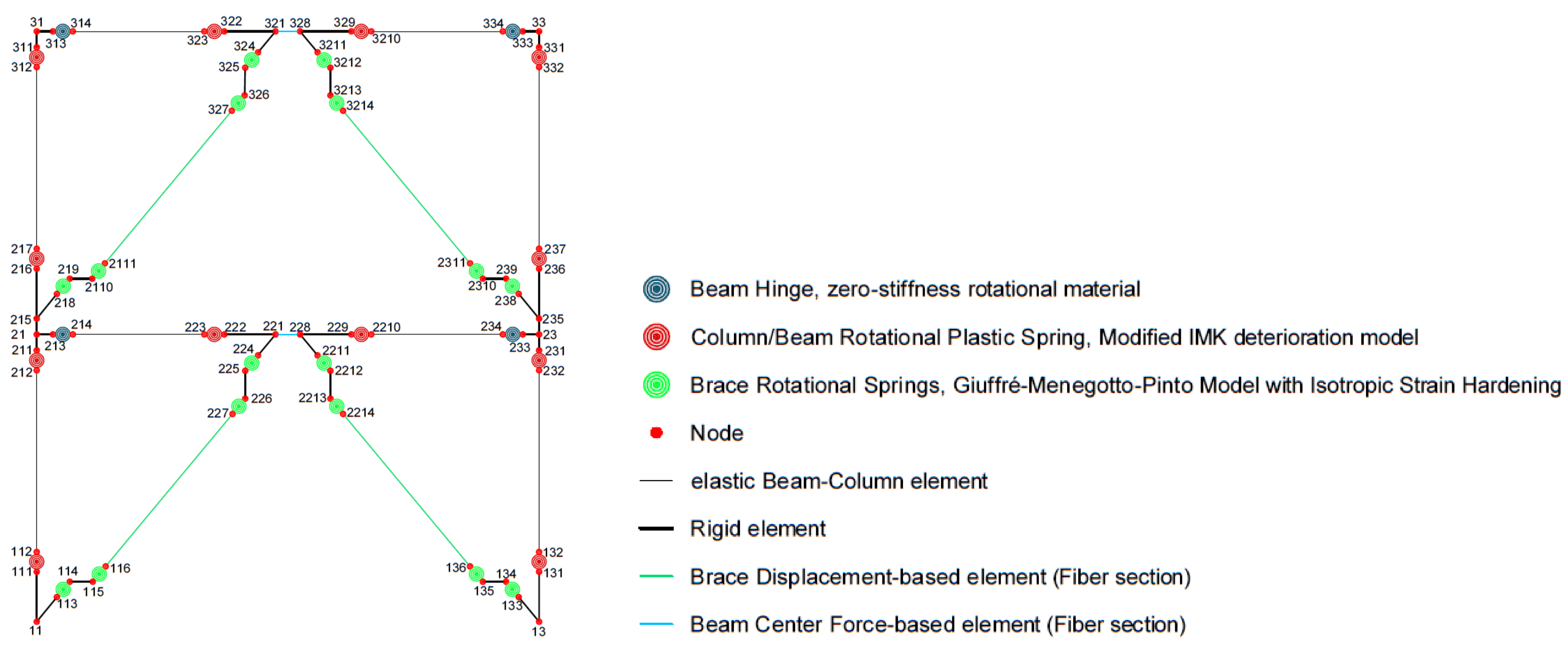


Fig. 5: Model of the initial structure

5. Non-Linear Static Analysis

- **The Braces can't develop their buckling and tensile resistance**
  - Due to premature fracture of the gusset plates

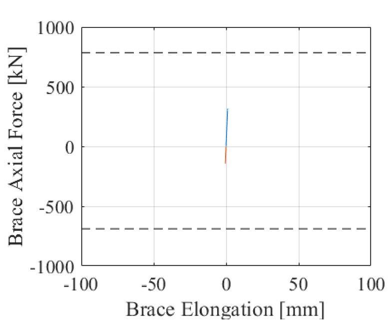


Fig. 6: 1st story Braces

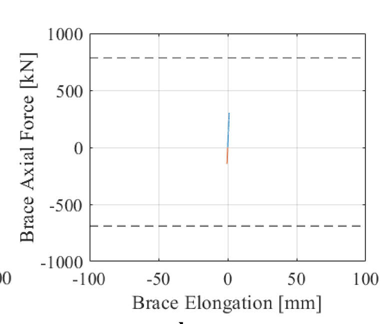


Fig. 7: 2nd story Braces

- **Assessment according to ASCE/SEI 41-13**
  - Target displacement: $\delta_t = 100\ mm$
  - Local Criteria:
    - *Braces*: do not fulfill any criteria
    - *Column rotation*: fulfill IO, LS, CP
    - *Beam rotation*: fulfill IO, LS, CP
- **Seismic retrofit is needed**

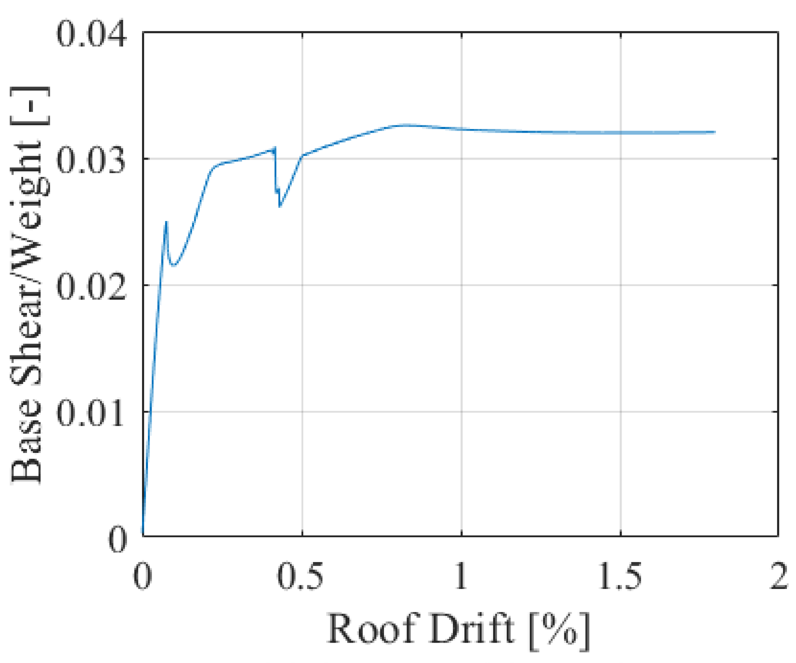


Fig. 8: Global response of the initial structure

6. Seismic Retrofit

6.1 Conventional seismic design

- **New Chevron Braces and Gusset plates**
  - According to the Capacity Design rules
  - 8-t_{GP} elliptical clearance

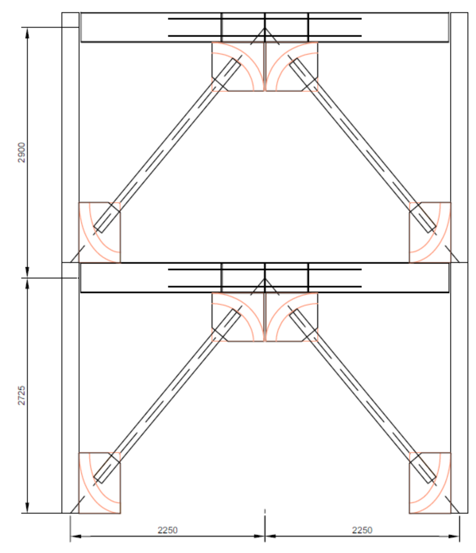


Fig. 9: new Chevron CBF

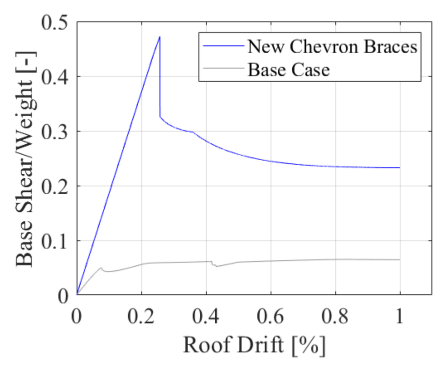


Fig. 11: Global response

- **Assessment according to ASCE/SEI 41-13**
  - Target displacement: $\delta_t = 8\ mm$
  - Local Criteria:
    - *Braces*: fulfill LS, CP
    - *Column rotation*: fulfill IO, LS, CP
    - *Beam rotation*: fulfill IO, LS, CP

- **New X-Braces and Gusset plates**
  - According to the Capacity Design rules
  - 8-t_{GP} elliptical clearance

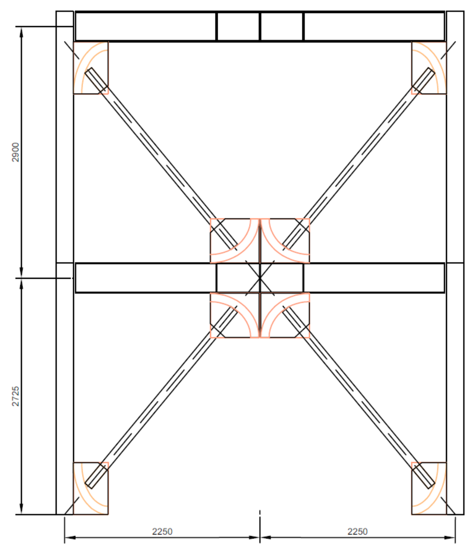


Fig. 10: new X-bracing CBF

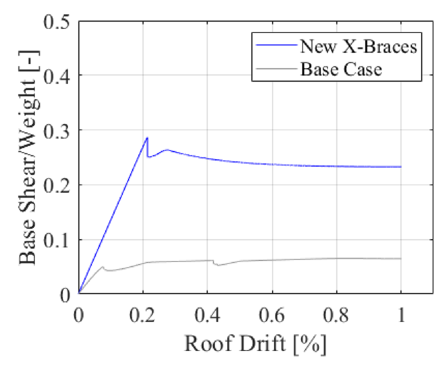


Fig. 12: Global response

- **Assessment according to ASCE/SEI 41-13**
  - Target displacement: $\delta_t = 18\ mm$
  - Local Criteria:
    - *Braces*: fulfill LS, CP
    - *Column rotation*: fulfill IO, LS, CP
    - *Beam rotation*: fulfill IO, LS, CP

6.2 High-performance system

- **Rocking Braced Frame**
  - Flag-shaped hysteretic response
  - Uplift of the column bases
  - Friction energy-dissipating devices
  - Needs the strengthening of the gusset plates

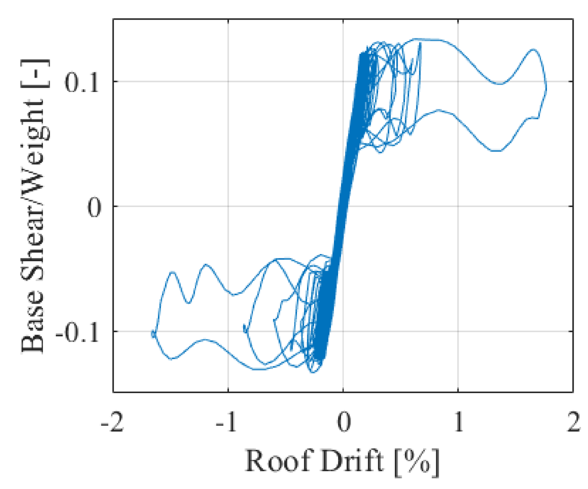


Fig. 13: Global response of the RBF

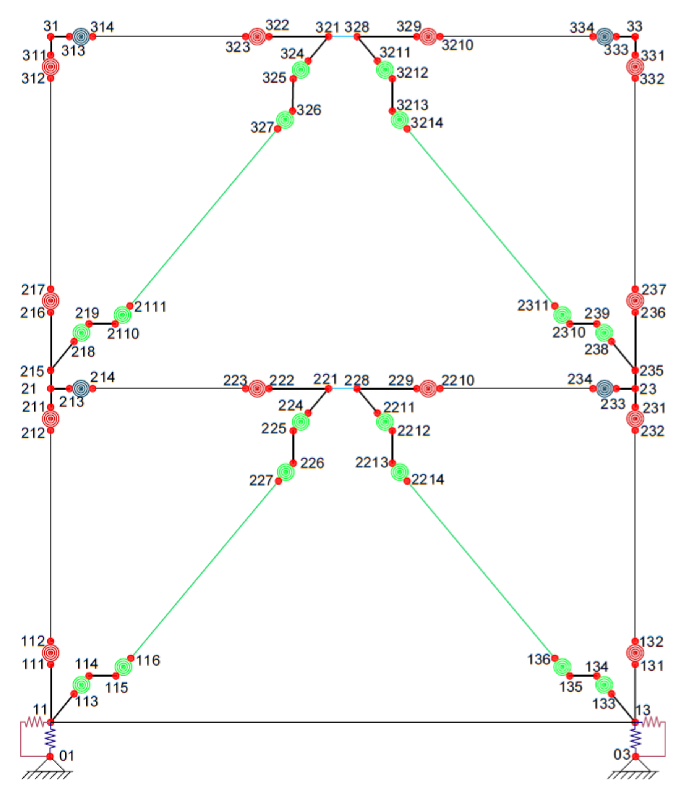
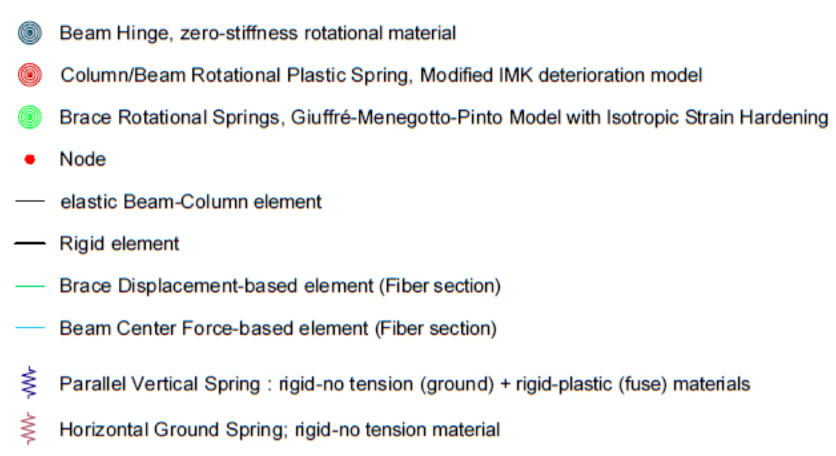


Fig. 14: Model of the RBF

			F_s = 200 kN
Fuse Yield Moment	M_{fsy}	[kNm]	900
Uplift Moment	M_{up}	[kNm]	3060
Flag height	M_{flag}	[kNm]	1800
Frame yield moment	M_y	[kNm]	3960
Overturning moment	M_u	[kNm]	4313
Self-centering	SC	[-]	4,53
Global Uplift	UL	[-]	4,53
Energy dissipation	ED	[-]	23%
Max. Uplift		[mm]	75



7. Non-Linear Dynamic Analysis

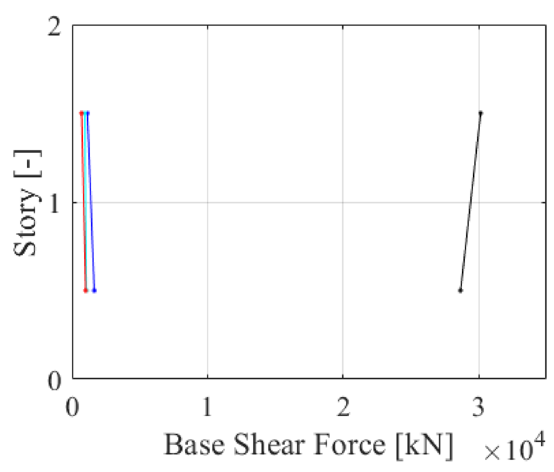


Fig 14.: Maximal Base Shear Force

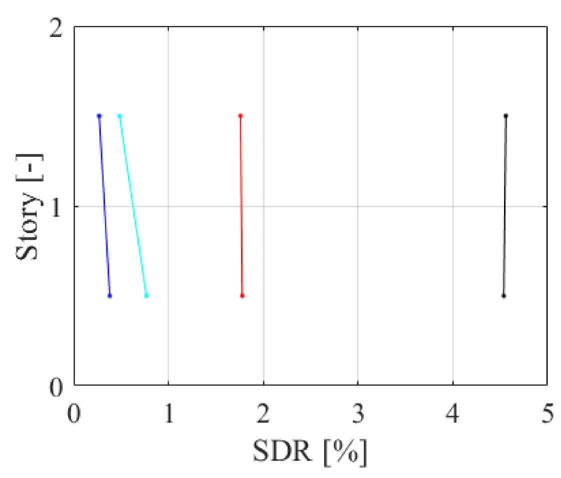


Fig. 15: Maximal Story Drift Ratio

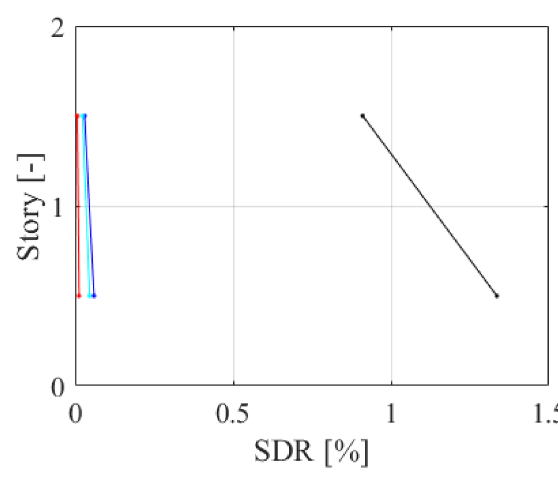
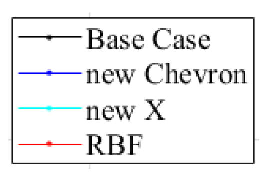


Fig 16.: Residual Story Drift Ratio



- **Comparison**
  - *Max. Base Shear Force*: Base case > new Chevron Braces > new X Braces > RBF
  - *Maximal SDR*: Base Case > RBF > new X Braces > new Chevron Braces
  - *Residual SDR*: Base Case > new Chevron Braces > new X braces > RBF
- **The RBF is the more performing system**
- **The RBF has the less retrofit effort and less damages after an earthquake**

Acknowledgment Prof. Dr. Dimitrios G. Lignos