Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Experimental Validation of Optimized Cast Steel Replaceable Modular Yielding Links for Eccentrically Braced Frames

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ABSTRACT

Steel casting technology has gained attention in earthquake engineering over the last decade, and recently, cast steel replaceable modular yielding links were proposed for use in eccentrically braced frames. Two design approaches have been adopted for the development of cast steel links. While in the first design approach, the links featured a constant effective length, the second design of links featured a design where a more consistent ductility capacity was targeted. This paper first provides an overview of the proposed cast steel links and summarizes the results from an experimental program at the University of Toronto for the experimental validation of cast steel links. The experimental setups and instrumentation are briefly presented. Selected results from the experiments are presented in terms of the link hysteretic response and the link axial response throughout the experiments. The experiments were used to characterize the overstrength of the proposed cast steel links. Additional phenomena such as the effects of axial loads and slab effects are also briefly discussed. The experiments demonstrated an excellent performance for the proposed cast steel yielding links. Given that the first generation of cast steel links targeted a constant effective length, the ductility capacity for links with different shear capacities varied across the product line with the maximum rotation capacities reaching as high as 0.21 radians for small to medium size links. The cast steel links designed for consistent ductility were able to sustain their target rotation of 0.15 radians.

Keywords: Steel Casting, Eccentrically Braced Frames, Yielding Links, Large-Scale Testing, Hysteretic Dampers

INTRODUCTION

Background on EBFs

Steel eccentrically braced frames (EBFs) are seismic force resisting systems (SFRS) with a large energy dissipation capacity and large lateral stiffness. The latter is owed to the presence of diagonal braces within the EBFs, while their energy dissipation is provided by inelastic deformations in a portion of the beam between the two braces, which is referred to as the yielding link. Such characteristics allows for EBFs to have an energy dissipation capacity comparable to Special Moment Resisting Frames (SMRFs), while exhibiting notable lateral stiffness that is comparable to Special Concentrically Braced Frames (SCBFs). EBFs were first proposed in Japan [1] and subsequently studied in the United States [2-8] as part of a comprehensive research project at the University of California, Berkeley. After the introduction of ASTM A992 steel into the steel industry, additional studies were performed on EBFs incorporating yielding links made of A992 steel [9-10]. Different aspects of EBFs have been studied over the years such as the use of built-up sections [11], the evaluation of the loading protocol for qualification of EBFs [12] and the use of other steel sections other than wide-flange sections (W-Sections) [13,14]. However, W-Sections are still the most commonly used steel profiles that are detailed as the yielding link in steel EBFs.

Depending on the yielding length (e_y) of the links in EBFs and the ratio of the link's plastic moment capacity (M_p) to its nominal plastic shear capacity (V_p), yielding links in EBFs are classified into: (1) Shear-critical links, (2) Flexural links, and (3) Intermediate links. While shear critical links undergo simultaneous yielding over the entire web region, flexural links form local plastic hinges at the two ends of the link. Therefore, shear-critical links are preferable. The advantage of shear-critical links over flexural links is also recognized by relevant design guidelines [15,16] where a larger maximum allowable rotation of 0.08 radians is allowed for shear-critical links, compared to the stricter limit of 0.02 radians for flexural links.

Limitations of EBFs

Despite their desirable characteristics, yielding links in EBFs must be detailed properly with web stiffeners, in order to ensure stable yielding of the web. In addition, controlling the link rotation requires design iterations for two reasons: (1) it is challenging to prevent the yielding of the beam outside of the link as they are formed by one member, and (2) finding a balanced design between the lateral drifts and link plastic rotations is not a trivial process. Lastly, the repair process in EBFs following a major earthquake is challenging, as the damaged yielding component is integral with the floor beam.

In order to address some of these challenges, replaceable links were proposed around a decade ago [14], which decouple the yielding link from the EBF beam allowing for a more convenient post-earthquake repair process. In addition, using replaceable links allow for a simplified design process as preventing the beam outside of the link from yielding is easier. These design advantages led to a wide interest in replaceable links particularly in the rebuilding of Christchurch [17]. However, replaceable links require stringent detailing requirements and are susceptible to the same failure mechanisms as conventional links, and therefore, their design rotation is limited to 0.08 radians.

Paper Objectives

In order to address the remaining limitations associated with EBFs, eliminate the detailing requirements for fabricated wide-flange replaceable links, and increase the rotation capacity of yielding links in EBFs, cast steel replaceable modular yielding links were recently developed and their performance was validated through an extensive experimental program at the University of Toronto. This paper provides a brief background on the design and the evolution of cast steel replaceable modular yielding links along with a summary of their experimental validation.

EVOLUTION OF CAST STEEL REPALCEABLE YIELDING LINKS

Background

The use of steel casting in structural engineering has increased in the last few decades given the advantages it offers. The freedom of geometry that is offered by steel castings allows engineers to propose complex shapes for an improved structural performance, which are not feasible with welded fabrication. In addition, steel casting reduces residual stresses and stress concentrations [18], and is a more economical option for fabrication of complex and mass-produced shapes [19]. In addition to the geometric optimization, steel casting allows for an optimized performance on a material level through heat treatment and comprehensive quality control. For these reasons, steel castings are a well suited for design and fabrication of energy dissipative hysteretic dampers [20].

Use of steel casting for fabrication of yielding links in EBFs was first proposed by Tan and Christopoulos [21], where finite element analyses were performed in order to find the optimal geometric design. Cast steel links with hollow box regions were proposed, where both depth and width of the hollow box regions tapered along the length. This design approach was used to achieve simultaneous flexural yielding under a double curvature moment diagram.

Cast Steel Replaceable Modular Yielding Links with Consistent Yielding Length

A detailed design of cast steel replaceable modular yielding links was provided by Mortazavi et al. [22]. Cast steel links are shown in Figure 1. As can be seen in Figure 1, cast steel links are formed by four primary regions: (1) the yielding regions comprised of a tapered hollow box such that it undergoes simultaneous yielding, (2) the elastic segment for transferring moment, shear, and axial forces, (3) the transition fillets, and (4) the integral cast endplates. The effective length (e_{eff}) of cast steel links, which is equivalent to the yielding length in conventional links is shown in Figure (1) as well. Figure 1 also shows the global configuration of cast steel links in an EBF, which are connected to the EBF beam with bolted endplates. In this first design approach nine sizes of cast steel links were detailed and proposed. As can be observed, the yielding links across the product line have a constant e_{eff}. The proposed cast steel links and their nominal plastic shear capacities (V_p) are shown in Figure 1. The naming convention includes the term "EBF" followed by the V_p of each link size in kips. The V_p values are also shown in kN in parentheses. Additional details regarding the design of the first generation of cast steel links is provided by Mortazavi et al. [22].

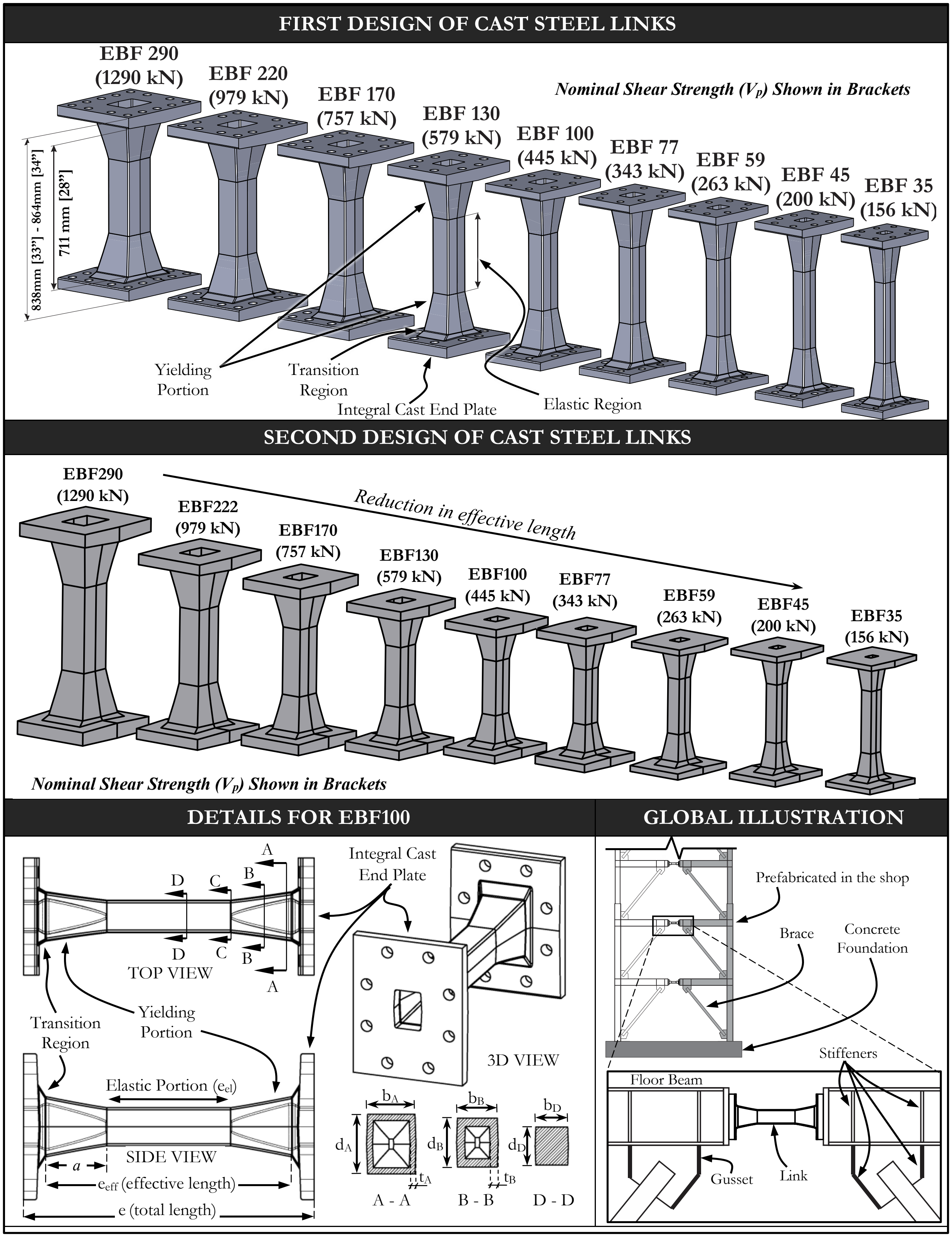


Figure 1. An overview of Cast Steel Replaceable Modular Yielding Links

Ductility-Targeted Cast Steel Replaceable Modular Yielding Links

In the second design approach, a slightly different design philosophy was adopted where the cast steel links were designed such that their e_{eff} varied across the product line. It has been shown that the ductility capacity and ULCF life of cast steel links are directly proportional to their e_{eff} and indirectly proportional to their V_p. [23] In other words, links with a larger shear capacity (but constant length) have a lower ductility, while links with a longer e_{eff} (and constant shear capacity) have a larger rotation capacity. Considering this, in the second design approach, the links were designed such that links with a larger shear capacity feature a longer e_{eff}, while smaller capacity links featured a shorter length. This was done in order to target a more consistent ductility capacity across the product line. Finite element analyses (FEAs) and a simple fracture estimation approach were directly considered in the design process to ensure that the e_{eff} of the links is selected such that their ductility capacity matched the targeted link rotation capacity. The cast steel links that were designed in this design iteration are shown in Figure 1. The design target rotation capacity is also shown in Table 1.

Final Cast Steel Replaceable Modular Yielding Links

The final product line of cast steel replaceable modular yielding links includes yielding links from both design iterations. The yielding links and selected specifications are shown in Table 1. The cast steel links, which are incorporated into the product line from the second design iteration include a "-S" at the end of their name, demonstrating that they have shorter e_{eff}. For instance, EBF45-S refers to a cast steel yielding link with a V_p of 45 kips, which is shorter in length. Table 1 also shows the overall length of the links including the endplates (e), the length of the yielding region (a), and the elastic stiffness of the links obtained from FEAs (K_{el}^{FE}). The design of cast steel links can be customized to accommodate a different V_p or target a larger rotation capacity, as per the project needs.

Table 1. Final Selection of Cast Steel Replaceable Modular Yielding Links

Link Designation	V_p [kips - kN]	e [mm]	e_{eff} [mm]	a [mm]	K_{el}^{FE} [kN/mm]
EBF-35	35 - 155.7	838.2	711.2	165.9	27.3
EBF-35-S	35 - 155.7	622.3	520.7	109.2	43.7
EBF-45	45 - 200	838.2	711.2	172.9	37.6
EBF-45-S	45 - 200	622.3	520.7	119.2	59.9
EBF-59	59 - 262	838.2	711.2	174.4	52.6
EBF-59-S	59 - 262	635.0	520.7	126.5	83.4
EBF-77	77 - 343	838.2	711.2	175.8	73.2
EBF-77-S	77 - 343	647.7	520.7	127.6	114.6
EBF-100	100 - 445	838.2	711.2	176.9	100.9
EBF-100-S	100 - 445	647.7	520.7	128.6	156.7
EBF-130	130 - 578	863.3	711.2	177.9	139.0
EBF-170	170 - 756	863.3	711.2	184.9	190.4
EBF-220	220 - 988	863.3	711.2	179.6	263.9
EBF-290	290 - 1290	863.3	711.2	180.3	360.4

EXPERIMENTAL TEST SETUPS

Two experimental setups were designed and fabricated for the experimental program, which are shown in Figure 2 and described in the following.

Component-Level Test Setup

The component-test setup, shown in Figure 2 (a), consisted of a self-equilibrating test setup in an MTS universal uniaxial testing frame with a force capacity of 2700 kN (610 kips), and a displacement capacity of ± 150 mm (6 inches). Steel members were designed and detailed such that the yielding links would be subjected to the same loading condition as they would be in an EBF (i.e., a constant shear force and a double-curvature linear bending moment), without any notable axial loads. The cast steel yielding links were connected to the specimen loading beams through their endplates using pre-tensioned high-strength bolts, as shown in Figure 2(a). The specimen loading beams were bolted to the loading beams, which were connected to the universal testing device through pin connections. All components and the connections were designed to be able to sustain loads associated with the setup capacity. Lateral supports were used to prevent any undesirable out-of-plane movements. Additional details regarding the design, detailing, and instrumentation of the component test setup are provided by Mortazavi et al. [24].

System-Level Test Setup

The frame test setup is shown in Figure 2 (b). The setup consisted of a one-story EBF equipped with a cast steel yielding link. The beams, columns, braces, and their connections were designed to be capacity protected for the probable capacity of the cast steel yielding link. The columns were pin-connected to base plates, which were connected to the laboratory strong floor using high-strength rods. The setup was loaded using two actuators with a total force capacity of 2000 kN (450 kips), and a displacement capacity of ± 340 mm (13.5 inches). The actuators were horizontally oriented and were connected to the EBF beam on the North side of the cast steel link while reacting against the laboratory strong wall. Given that the actuators impose displacements on the setup from one side, the cast modular links tested in the frame test setup were loaded with axial loads in conjunction with shear forces and bending moments. The frame setup was designed such that the ratio of link axial load to link shear force was approximately 1.11 throughout the experiments. Lateral supports were provided for the frame setup in order to avoid any undesirable out-of-plane movements during testing. Additional details regarding the design, detailing, and instrumentation of the frame test setup are provided by Mortazavi et al. [24].

(a) (b)

Figure 2. Experimental Setups: (a) Component-Level Test Setup, and (b) System-Level Test Setup

EXPERIMENTAL RESULTS

Tested Specimens

The specimens that were tested in the experimental program are shown in Tables 2 and 3. Eight cast steel yielding links were tested in the component test setup. The experiments included tests on the largest links, the medium size links, and the smallest links. In addition, two link sizes from the S-series links were tested. Four link sizes were tested in the frame setup, which are summarized in Table 3. In addition, the frame test was repeated for one of the specimens (i.e., EBF100) with a composite concrete slab to assess the effects of a concrete slab on the response of yielding link.

Table 2. Summary of Experiments Performed in the Component Setup

Test No.	Test Name	Specimen	Heat	Foundry	Protocol
1	EBF35-1	EBF35	H1	F1	AISC 341
2	EBF35-2	EBF35	H2	F1	AISC 341
3	EBF77	EBF77	H3	F2	AISC 341
4	EBF100	EBF100	H4	F2	AISC 341
5	EBF290-1	EBF290	H1	F1	AISC 341
6	EBF290-2	EBF290	H2	F1	AISC 341
7	EBF45-S	EBF45-S	H5	F3	AISC 341
8	EBF59-S	EBF59-S	H6	F3	AISC 341

Each experiment is assigned a unique code, which includes the name of the cast steel link specimen. For repeat experiments, a number is added to specimen specification to distinguish between the tests. Frame tests, which are shown in Table 3, are identified by adding the letter F at the end of the specimen specification. The frame test with the slab is shown with the specimen specification with letters FS. The cast steel heat (H) for each specimen is also provided in Tables 2 and 3. The Tables also distinguish the specimens based on the foundry where they were cast. As shown in Tables 2 and 3, all specimens were subjected to the AISC 341 [15] loading protocol for prequalification of yielding links in EBFs.

Material Properties

The structural properties for each cast steel heat, as reported by the foundries, are provided in Table 4. Additionally, in order to characterize the compressive strength (f_c') of the composite concrete slab, concrete cylinders were cast from the same concrete pour as the structural slab and tested. The f_c' for the concrete slab was determined to be 33.4 *MPa*.

Table 3. Summary of Experiments Performed in the Frame Setup

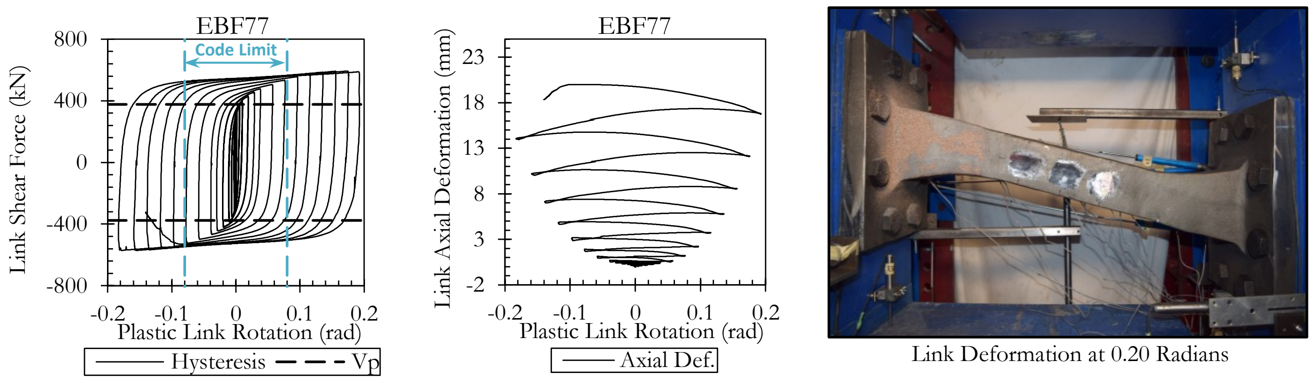
Test No.	Test Name	Specimen	Slab	Heat	Foundry	Protocol
9	EBF77-F	EBF77	No	H3	F1	AISC 341
10	EBF100-F	EBF100	No	H4	F1	AISC 341
11	EBF100-FS	EBF100	Yes	H4	F2	AISC 341
12	EBF45-S-F	EBF45-S	No	H5	F3	AISC 341
13	EBF59-S-F	EBF59-S	No	H6	F3	AISC 341

Table 4. Cast Steel Heat Properties

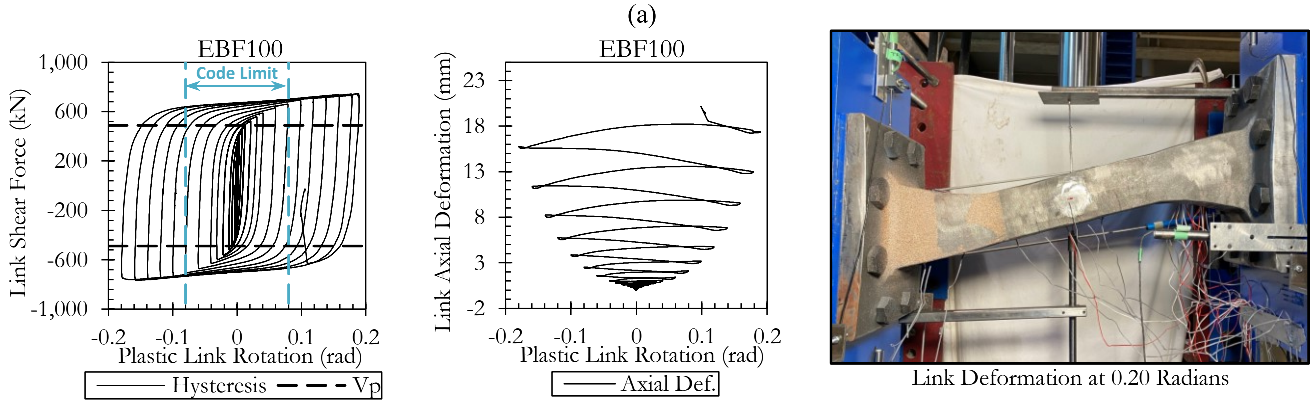
Cast Steel Heat	F_y (MPa)	F_u (MPa)	Foundry
H1	299	459	F1
H2	320	471	F1
H3	299	517	F2
H4	317	507	F2
H5	318	465	F3
H6	303	468	F3

Sample Results from Component-Level Tests

Results from component tests on EBF77 and EBF100 cast steel links are provided in Figure 4, in terms of link hysteretic response, link axial deformation, and the link's deformed shape during the last cycle of the experiments. Key response parameters from the remaining component test results are provided in the Summary of Experimental Results Section.



(a)



(b)

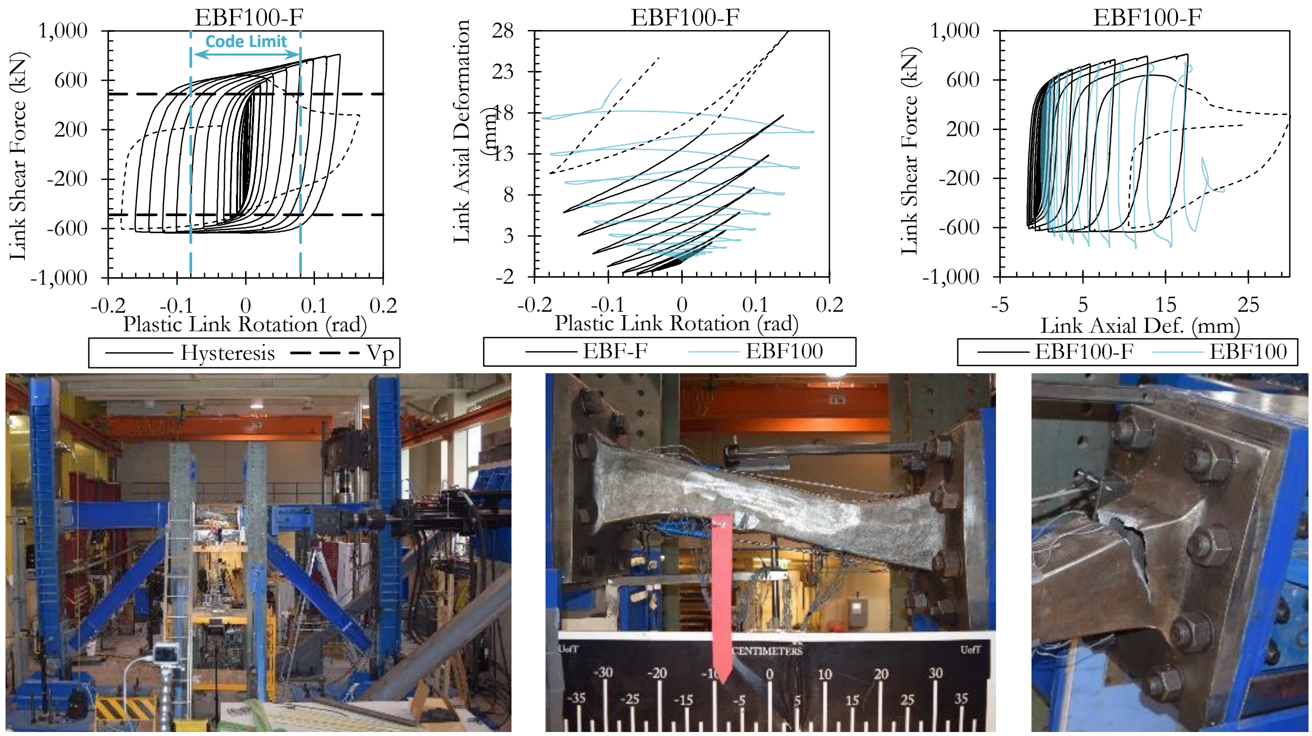
Figure 3. Sample Test Results from Component-Level Experimental Validations: (a) Results from the EBF77 Test, and (b) Results from the EBF100 Test

Sample Results from System-Level Tests

Results from frame tests on the EBF100 cast steel link with and without the concrete slab are provided in Figure 4. The results include the link's hysteretic response, the link's axial deformation, and the link's deformed shapes. Key response parameters from the remaining component test results are provided in the Summary of Experimental Results Section.

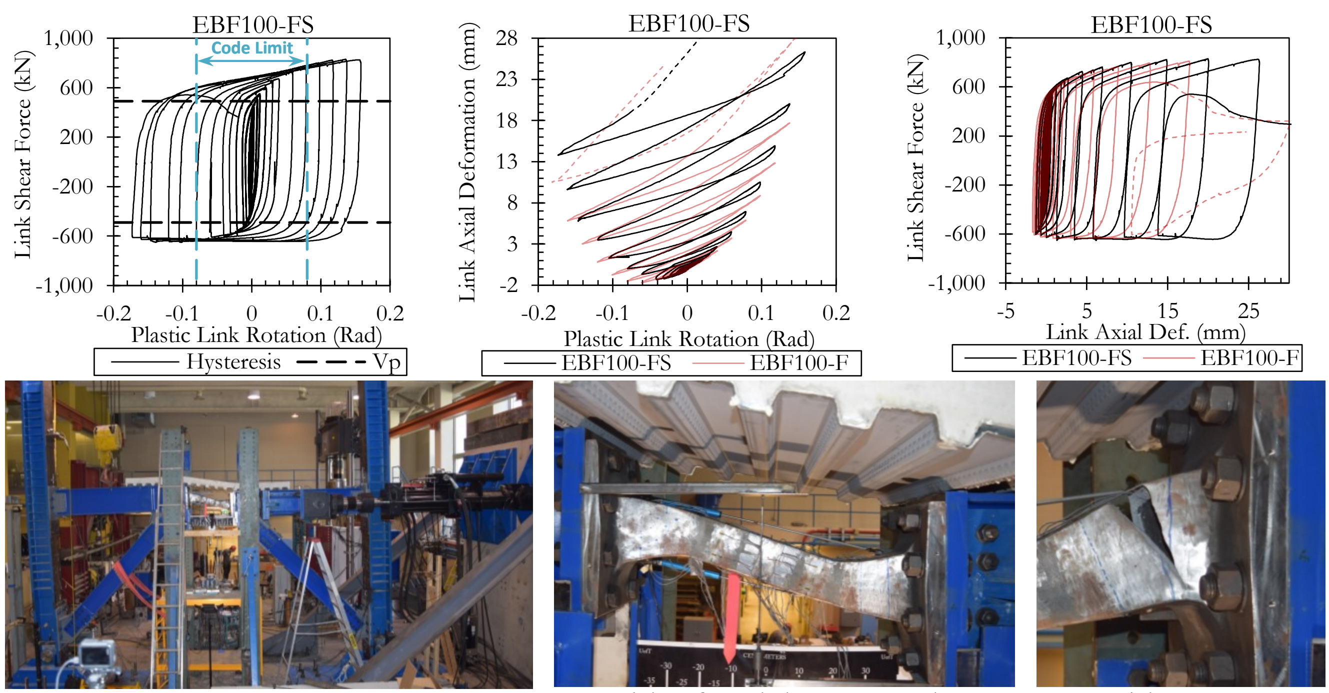
Overstrength Characterization

Results from the component-level tests were used to characterize the link overstrength. For this purpose, the maximum link shear at each cycle (V_Θ) was divided by the link V_p in order to obtain the link overstrength at each cycle ($\omega = V_\Theta / V_p$). The change in ω with respect to link rotation is shown in Figure 5 for EBF35s, EBF77, EBF100, and EBF290s, as sample results.



Frame Deformed Shape at 0.17 rad | Link Deformed Shape at 0.17 rad | Link Fracture

(a)



Frame Deformed Shape at 0.19 rads | Link Deformed Shape at 0.19 rads | Link Fracture

(b)

Figure 4. Sample Test Results from Frame-Level Experimental Validations: (a) Results from the EBF100-F Test, and (b) Results from the EBF100-FS Test

It must be noted that in each rotation cycle, two values of ω are obtained, which do not always match due to asymmetry, self-weight, etc. The larger value is shown as ω_{max} and the lower value is referred to as ω_{min}. Both are shown in Figure 5. The largest ω values obtained in the last cycle of the response for all yielding links are presented in the Summary of Experimental Results Section.

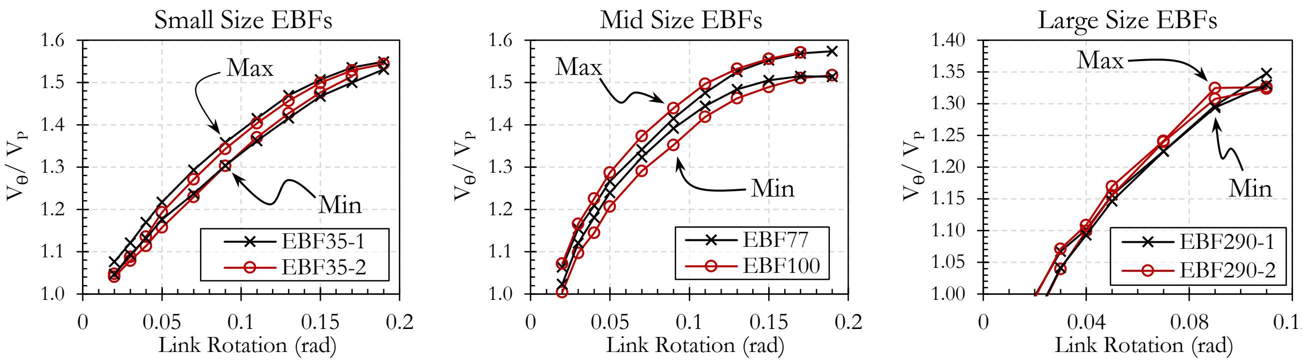


Figure 5. Sample Overstrength Characterization for EBF35s, EBF77, EBF100, and EBF290s

Axial Load Effects

Other than providing an opportunity to study the global response of EBFs equipped with cast steel replaceable modular yielding links, the frame tests allowed for studying the effects of axial loads on the response of yielding links in EBFs. The frame test setup was designed such that it would induce an axial load equal to $1.11V_{Link}$ in the yielding links, where V_{Link} is the link shear force at any given time during the response. The axial load as a percentage of link's axial yield force, varied for different links. Given the setup configuration and the placement of the actuators, the yielding links were in compression for half a cycle, and in tension for the other half cycle. Axial load effects on the response of the links are briefly reviewed in the following. Additional details about axial load effects and how it affects the response of yielding links is provided by [25-27].

The results from the frame tests demonstrated that axial tension increased the link shear, while axial compression decreased the link shear strength. This is similar to what had been observed in previous studies for conventional yielding links. Figure 6 shows the hysteretic response from the component test, where the yielding link experienced no axial loading, and the hysteretic response from the frame tests, where the yielding links experienced an axial load equal to $1.11V_{Link}$.

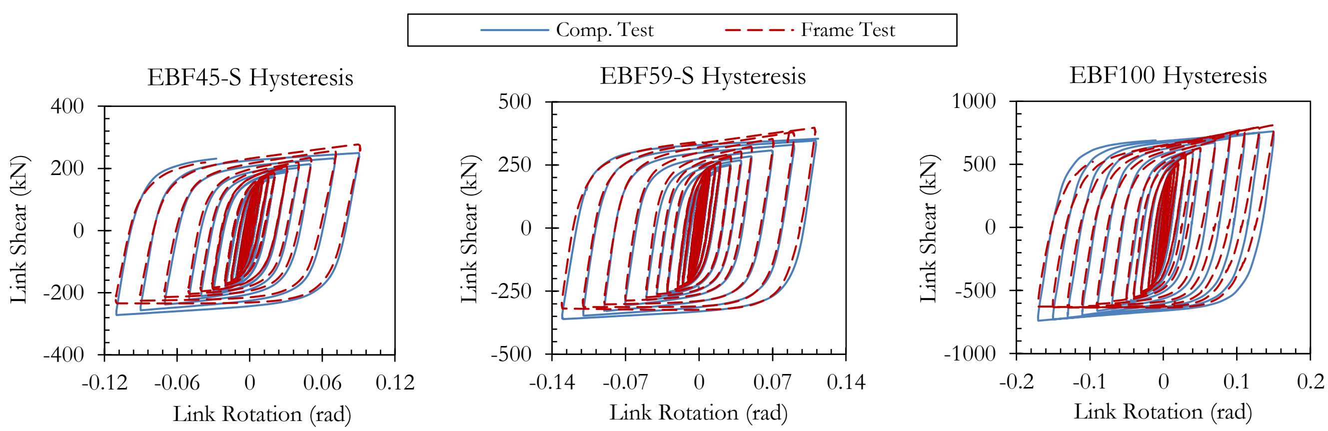


Figure 6. Effect of Axial Loading on the Hysteretic Response for EBF45-S, EBF59-S, and EBF100

The presence of axial loads also reduced the ULCF life of the yielding links. In all frame tests it was observed that the ULCF life of cast steel yielding links were reduced by one to two cycles, compared to the component test on the same specimen. Additional details regarding the effects of axial loading on the response of cast steel yielding links is provided in [22].

Concrete Slab Effects

The presence of a concrete slab marginally increased the shear force at the link location, in the initial cycles at small rotations. However, as the frame setup was loaded laterally, the concrete slab further cracked which reduced its contribution to the overall shear load in the system. Therefore, including the effects of concrete slab for the design of the capacity-protected elements in

EBFs is likely not necessary. However, additional experiments with different link sizes and concrete slab thickness values are required to confirm this.

The presence of the concrete slab was observed to increase the loading and unloading stiffness in the system. Therefore, in EBF buildings housing sensitive equipment which are sensitive to acceleration, the effects of concrete slab may have to be considered in quantifying the system's stiffness. Additional details regarding the concrete slab and its effect on the response of the system is provided by [22].

SUMMARY OF EXPERIMENTAL RESULTS

Table 5 provides a summary of experimental results obtained from all experiments. Key response parameters for each experiment are reported. Depending on the experiment, maximum link rotation (γ), maximum plastic link rotation (γ_p), the frame drift (Θ), ω_{max}, reduction in link shear under axial compression (ω_C), increase in link shear under axial tension (ω_T), and increase in link capacity due to the presence of a concrete slab in tension and compression cycles (ω_{Slab-T} and ω_{Slab-C}) are reported.

Table 5. Summary of the Experimental Program

Test Name	γ	γ_p	Θ (%)	Cycle*	ω_{max}	ω_T	ω_C	ω_{Slab-T}	ω_{Slab-C}
EBF35-1	0.19	0.182	N/A	2.5	1.55	-	-	-	-
EBF35-2	0.19	0.181	N/A	1.5	1.54	-	-	-	-
EBF45-S	0.15	0.141	N/A	0.5	1.62	-	-	-	-
EBF59-S	0.15	0.142	N/A	0.5	1.52	-	-	-	-
EBF45-S-F	0.11	0.103	1.03	0.5 (C)	-	1.10	0.88	-	-
EBF59-S-F	0.13	0.123	1.20	0.5 (C)	1.62	-	-	-	-
EBF77	0.21	0.193	N/A	0.5	1.57	-	-	-	-
EBF77-F	0.17	0.158	2.07	0.5 (C)	-	1.07	0.77	-	-
EBF100	0.20	0.190	N/A	0.5	1.57	-	-	-	-
EBF100-F	0.17	0.152	2.07	0.5 (C)	-	1.09	0.80	-	-
EBF100-FS	0.19	0.173	2.22	0.5 (C)	-	-	-	1.04**	1.03**
EBF290-1	0.11	0.105	N/A	1	1.35	-	-	-	-
EBF290-2	0.11	0.105	N/A	1	1.33	-	-	-	-

**Shows the number of cycles performed at maximum reported rotation (i.e., 0.5 (C): half the cycle was completed with the link in compression)*
***Slab overstrength reported for a link rotation of 0.09*

CONCLUSIONS

This paper provides an overview of cast steel replaceable yielding links, their evolution, and their extensive experimental validation. A brief background on EBFs was first provided. Different designs of cast steel replaceable yielding links were presented and reviewed. The test setups used in the experimental program, namely a component-level test setup and a frame-level test setup were presented and discussed. Selected test results from the component- and frame-level experimental validations were provided. Different phenomena including the overstrength characterization, the effects of axial load on the response of yielding links, and the effects of a concrete on the response were discussed. The study leads to the following conclusions.

- The maximum rotation capacity of cast steel yielding links is beyond the code prescribed rotation limit on conventional and fabricated replaceable yielding links in eccentrically braced frames.
- The cast steel links with a small to medium shear capacity, with longer effective lengths demonstrated a very large rotation capacity sustaining rotations beyond 0.19 radians. The "S" series cast steel yielding links, which were designed with a shorter length were able to reach the targeted rotation of 0.15 radians. The EBF290s were able to sustain a more moderate rotation of 0.11 radians. This reduction in rotation capacity was expected as it has been previously shown that the rotation capacity of cast steel links is inversely proportional to their shear strength and directly proportional to their effective length [22,23]. In other words, for a constant effective length, yielding links with a larger capacity will have a lower rotation capacity. In addition, for a constant shear strength, the yielding link with a longer effective length has a higher rotation capacity. The design of cast steel yielding links may be customized to target a different rotation capacity, as per the project requirements.
- Results from the component-level experimental validation demonstrate a stable response for cast steel yielding links.
- The component-level test results were used to characterize the link overstrength, which showed that the cast steel yielding links have comparable overstrength with conventional and fabricated replaceable links.

- Results from the frame tests demonstrated that the link shear increases under tension loads and is reduced under compressive loads, which is consistent with what has been observed for conventional links.
- The ultimate rotation of cast steel links from each test are shown in Table 5. The presence of axial loads reduced the ULCF life of the cast steel yielding links. The rotation capacity of cast steel links tested in the frame setup were reduced by one to two cycles, compared to their rotation capacity in the component test setup.
- The concrete slab was observed to increase the stiffness of the loading/unloading branches of the hysteretic response.

ACKNOWLEDGMENTS

The authors acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) [ALLRP 560261-20] and Ontario Centres of Excellence (OCE VIP II-27058).

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