Loading protocols employed in evaluation of seismic behavior of steel beams in weak-beam moment frames

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SUMMARY:
The plastic deformation capacity of beams before ductile fracture is one of the most popular topics in seismic design of steel moment frame. Seismic effects of significantly different characteristics are applied to beams during distinct earthquakes. The loading protocols employed in beam tests to evaluate its seismic behavior have been studied by researchers universally for decades. Basically, each country has its own standard loading protocols for steel beam testing. However, it is doubtful whether the current loading protocols are enough to represent real beam behavior in frames during earthquakes. This paper estimates the currently used loading protocols and gives suggestions on the selection of the loading protocols in beam testing. The beams' behavior under the present loading protocols was compared with that under analytical beam responses. The appropriate combinations of the loading protocols employed in beam tests for the purpose of evaluating the seismic behavior of steel beams were suggested.

Keywords: Steel beam, Loading protocol, Ductile fracture, Response analysis, Beam analysis

1. INTRODUCTION

Steel moment frames with strong-column weak-beam mechanism are frequently used in earthquake-prone areas. In such systems, beams are the dominant anti-earthquake components that dissipate the majority of the earthquake input energy. Therefore, the evaluation of the seismic behavior, i.e., plastic deformation capacity of beams before ductile fracture is one of the most popular topics in seismic design of steel structures.

Seismic effects of significantly different characteristics are applied to beams during distinct earthquakes. Furthermore, the number and amplitudes of the loading cycles the beam experiences during earthquakes depend on the configuration, strength, stiffness, etc. of the structure. The loading protocols employed in beam tests to evaluate its seismic behavior have been studied by researchers universally for decades. Basically, each country has its own standard loading protocols for steel beam testing. For example, the AISC 2005(AISC 2005) protocol is used in the USA, and the JISF (JISF 2002) loading protocol is accepted in Japan. However, it is doubtful whether the current loading protocols are enough to represent real beam responses in structures during earthquakes. This paper tries to evaluate the currently used loading protocols and gives suggestions on the selection of the loading protocols in beam testing.

The first part of this paper studies beam response in a weak-beam moment frame during different earthquakes. Response analyses (Yamada et al. 1994, 1996) of a plane moment frame were conducted under eleven ground motions. Earthquake records with distinct characteristics such as the JMA Kobe record, Hachinohe record, and the JMA Sendai record, etc., were input into the frame analyses. The beam responses during each earthquake were obtained.

The second part of this study compares the beam's seismic response with the presently used loading protocols. According to the recent study, under cyclic loadings, the stress-strain histories till fracture at the beam flange fracture zone (close to the connection) can be obtained through in-plane beam analyses (Yamada et al. 2011). The growing process of the cumulative plastic strain ratios (CPSR) calculated from the stress-strain relationship shows strong correlation with the characteristics of loading histories. Therefore, the in-plane beam analyses of beams subjected to different loading histories were carried out in this study. The input loading histories were the beam responses obtained from the frame response analyses and the commonly employed American and Japanese beam testing loading protocols. The beams' behavior under the present loading protocols was compared with that under real beam responses. The appropriate combinations of the loading protocols employed in beam tests for the purpose of evaluating the seismic behavior of steel beams were suggested.

2. BEAM PERPORMANCE IN A WEAK-BEAM MOMENT FRAME DURING VARIOUS EARTHQUAKES

2.1. Steel Plane Frame Employed in the Response Analysis

The four-storied four-span plane frame (response analytical model) is picked up from a steel building designed as a design example in one Japanese text book (Gihoudo 2009), which is designed based on the current Japanese design code. The elevation and the analytical model of this frame are shown in Figure 1. Typical welded beam-to-column connections are used in this frame. Structural details of the weak-beam moment frame are listed as follows.

Beam: H 500×200×10×16 (SN400B) Column: RHS 350×350×19 (BCP 325)
Exposed type column base: Baseplate: 650×650×60 (SN490B)
Anchor bolts: 8-M42 (ABR 400), lb=1200mm

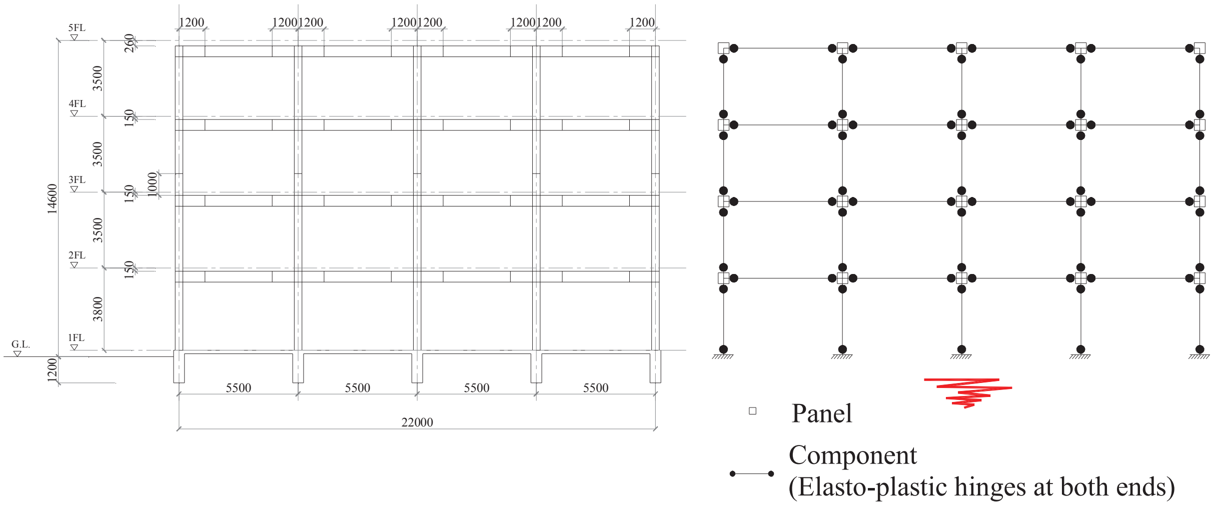


Figure 1. Analytical model of the plane frame response analysis

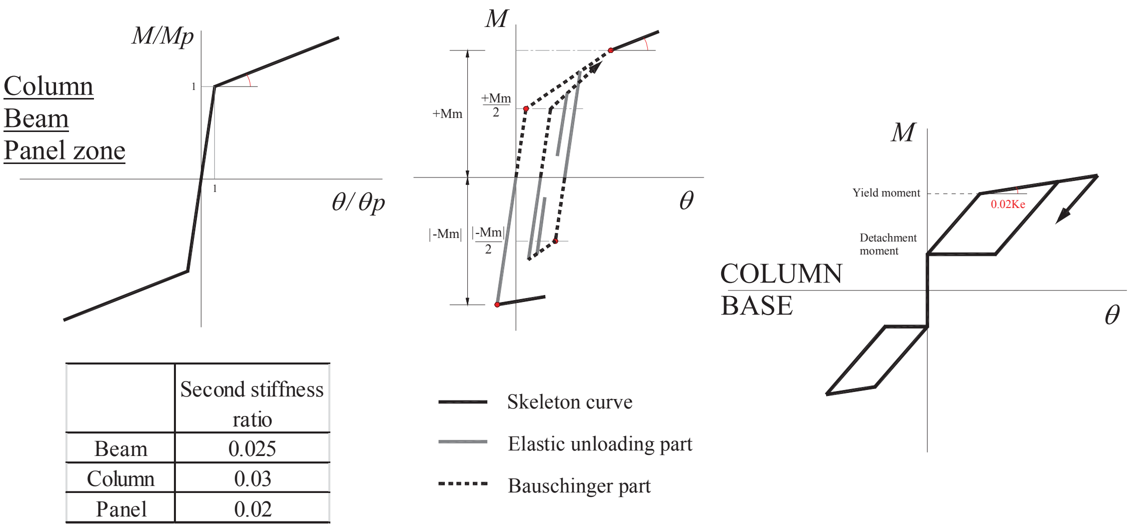
2.2. Hysteresis Model of Each Structural Component

In the response analysis, the hysteresis model employed for each structural component is shown in Figure 2. The multi-linear moment-rotation hysteresis model considering Bauschinger effect (Akiyama et al. 1990) is employed for each of the structural component (beam, column, and panel zone). The second stiffness ratio of the skeleton curve of the beam is set to 0.025. The columns skeleton curve has the second stiffness ratio of 0.03, while that of the panel zone is 0.02. The hysteresis model of the column base is also shown in Figure 2. Detachment moment and the strength (maximum moment) were calculated from the frame model. Therefore, the side column base and the middle column base have different strengths. The second stiffness ratio is set to be 0.02.

2.3. Response analysis methodology

Constant average acceleration method (elasto-plastic system) is introduced in the response analysis with $\beta = 1/4$. Reyleigh damping ratio for the first and second modes are 0.02. The P-Δ effect of the frame is also considered as minus stiffness in this analysis (Akiyama 1984).

The bending deformation of each component (beam/column) concentrates at the elasto-plastic hinges located at both ends of the component. The axial stiffness of the component is considered to remain elastic during the analysis. Shear deformation of the panel zone is also considered. The deformation condition of the beam-to-column joint is shown in Figure 3.



	Second stiffness ratio
Beam	0.025
Column	0.03
Panel	0.02

Figure 2. Hysteresis model of the components

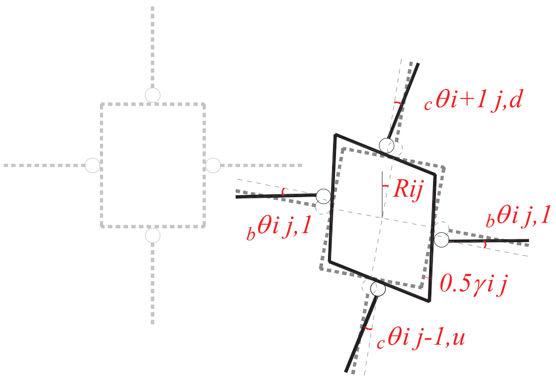


Figure 3. Deformation condition of the beam-to-column joint

2.4 Input Earthquake Ground Motions and the Scaled Factor

Ground motions of significantly different characteristics were input into the structures during earthquakes. Both the characteristics of the earthquake (such as the magnitude, fault type, depth of focus, soil type, etc.) and the characteristics of the structures (natural period, damping condition, strength of the components, etc.) would affect the beams seismic responses. In weak-beam moment frames, the plastic hinges form at the end of the beams close to the beam-to-column connections, and dissipate most of the seismic input energy.

In this research, the frame analytical model is fixed. A set of 11 strong ground motion records, listed in Table 1, is used to evaluate the beams seismic performance in a weak-beam moment frame. According to the current researches on the structural performance of frames under earthquakes, the ground motion records used in a response analysis should cover as more types of earthquake records as possible. This group of ground motion records includes the oceanic trench-type record (Hachinohe), the near fault earthquake record (Kobe, Northridge, etc.) and the long-duration earthquake record (Touhoku). Based on the eigenvalue analysis, the natural period of the frame model is 0.59s.The energy spectrum till period of 2s are presented in Figure 4. The natural period of the frame model is shown in the figure.

The beams responses under three levels of input earthquake records are investigated in this research. This research studies the plastic deformation capacity of steel beam under earthquake effects. Therefore, the basic scaled factor (BSF) is the factor with which the beam with largest response reaches ductile fracture just at the end of the earthquake record. The fracture point is determined through the evaluation method suggested in (Yamada et al. 2011). The other two factors are 0.8×BSF and 1.2×BSF, respectively. The scaled factors of all three levels are listed in Table 1.

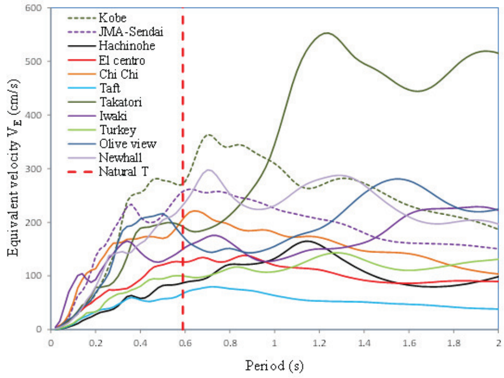


Figure 4. Energy spectrum of the ground motion records (Elastic SDOF system, damping ratio 0.1)

Table 2.1. Basic Properties of Recorded Ground Motions and the Scaled Factors

EARTHQUAKE	RECORDED STATION	MAGNITUDE	DIRECTIO N	DURATIO N (s)	FRACTUR E INPUT LEVEL	FRACTUR E INPUT LEVEL×0.8	FRACTURE INPUT LEVEL×1.2
Kobe, Japan, 1995	JMA Kobe	7.2	NS	30	1.06	0.848	1.272
Kobe, Japan, 1995	Takatori Eki	7.2	NS	40.96	1.152	0.9216	1.3824
Northridge, US, 1994	Olive View	6.7	360	40	2.43	1.944	2.916
Northridge, US, 1994	Newhall	6.7	360	40	1.396	1.1168	1.6752
Tokachi-oki, Japan, 1968	Hachinohe	7.9	EW	36	3.8	3.04	4.56
Imperial Valley, US, 1940	El-centro	7.0	NS	53.76	3.81	3.048	4.572
Taft, US, 1952	Taft	7.4	NS	54.38	6.6	5.28	7.92
Chi chi, Taiwan, 1999	Shuili	7.6	78	90	24	19.2	28.8
Kocaeli, Turkey, 1999	Yarimca	7.8	EW	135	3.85	3.08	4.62
Touhoku, Japan, 2011	K-net Iwaki	9.0	EW	180	3.014	2.4112	3.62
Touhoku, Japan, 2011	JMA Sendai	9.0	NS	180	1.995	1.596	2.394

2.5 Beam Response Obtained from the Response Analyses under Various Earthquakes with Different Scaled factors

The results of the response analyses, i.e., the beam responses under 11 ground motion records with three scaled factors are obtained. As examples, Figure 5 shows several of the responses of the beam at BSF with largest beam response in the analysis under each ground motion.

The difference of the beam response till fracture from different earthquakes can be found from these graphs. Under near-fault earthquakes (Takatori, Olive View, etc.), the beam fractured after several large amplitude cycles. While under long-duration ground motions (Turkey, Iwaki, etc.), there are a large amount earthquake loading cycles that the beam experienced before fracture. The amplitudes of the loading cycles are usually smaller than that under near-fault ground motions. The maximum beams' responses in the plane steel frame were obtained from the response analyses. The plastic ratios μ , which represents the maximum beam rotation are shown in Figure 6. The plastic ratios grow with the increase of the input scaled factor. Under same input scaled factor, the beam's plastic ratios under near-fault earthquakes are larger than those under other types of earthquake ground motions, especially the ones under long-duration ground motions.

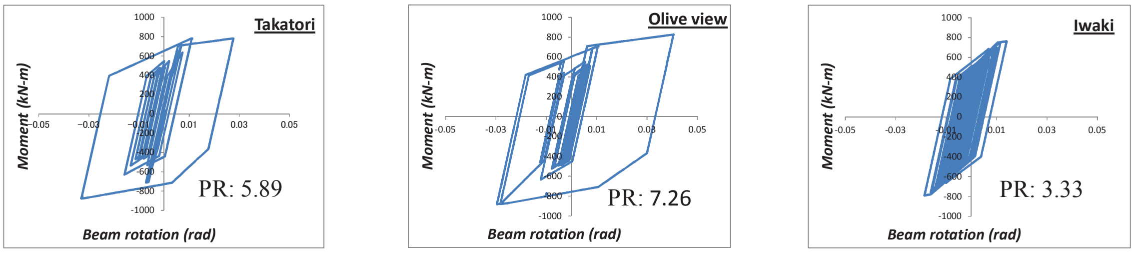


Figure 5. Examples of the maximum beam response

2.6. Beam Behavior under Various Earthquake Ground Motions

Referring to the evaluation method of the beam's plastic deformation capacity from (Yamada et al. 2011), the cumulative plastic strain ratio at the toe of the weld access hole on the fractured flange of the beams under each ground motion record was also output from the analyses (${}^m\eta_S{}^+, {}^m\eta_S{}^-, {}^m\eta_B{}^+, {}^m\eta_B{}^-$). The growing processes of ${}^m\eta_S{}^+ / {}^m\eta_0$ and ${}^m\eta_T / {}^m\eta_0$ of all beams subjected to different ground motions with 3 levels of scaled factors are plotted in Figure 6. The fracture condition (Yamada et al. 2011) is also plotted in Figure 6. These graphs indicate that:

1) The growing processes of plastic strain ratio of the beams under different ground motion records are quite different. Under long-duration ground motions such as the K-net Iwaki record, till ductile fracture, beams tend to have larger cumulative plastic strain ratios with smaller skeleton cumulative plastic strain ratios. The growing process of plastic strain ratio goes along the left side of the graph. On the other hand, under near-fault ground motions like Olive record and Kobe record, the growing process of plastic strain ratio goes along the right side of the graph, when the overall plastic strain ratios are smaller but the skeleton plastic strain ratios are larger. For the rest of the ground motion records, the growing process of plastic strain ratio cover almost evenly between the two types of earthquakes mentioned above.
2) Under ground motion input with larger BSF, the growing processes of plastic strain ratio tend to lean toward the right side of the graph. In other word, the overall plastic strain ratios become smaller while the ratio of ${}^m\eta_S{}^+ / {}^m\eta_0$ to ${}^m\eta_T / {}^m\eta_0$ grow larger.
3) Under ground motion input with smaller BSF, the growing processes of plastic strain ratio tend to shrink to the middle of the graph. Both the overall and skeleton plastic strain ratios become smaller.

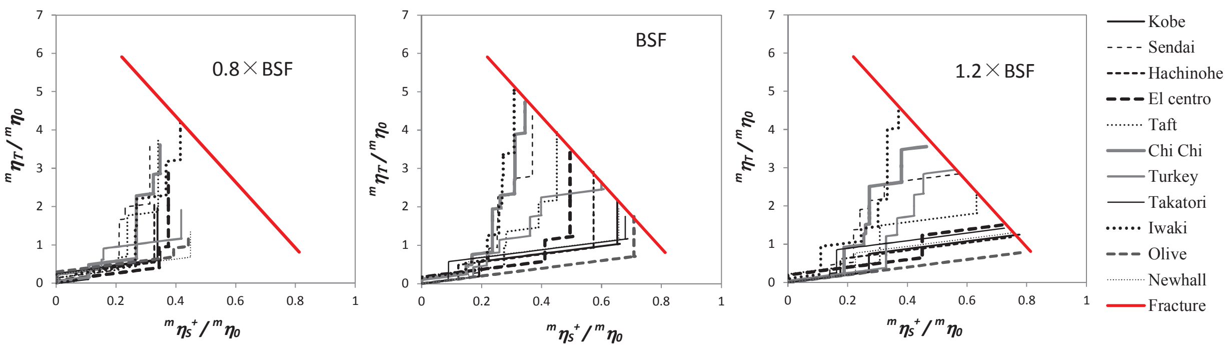


Figure 6. Plastic strain ratio growing processes of the beams under three levels of scaled factors

3. RECOMMENDED LOADING PROTOCOLS IN JAPAN AND THE UNITED STATES

3.1 JISF Loading Protocols

Figure 7 shows the loading protocol recommended by the Building Research Institute and the Japan Iron and Steel Federation (JISF 2002), which is commonly accepted in Japan. This loading protocol is obtained through the response analyses of frames. The incremental cyclic loading starting from $\pm 2\theta_P$, with intervals of $2\theta_P$, where θ_P the elastic beam rotation when the moment of the beam's cantilever end equals its full plastic moment M_P. For each loading step, two cycles should be applied.

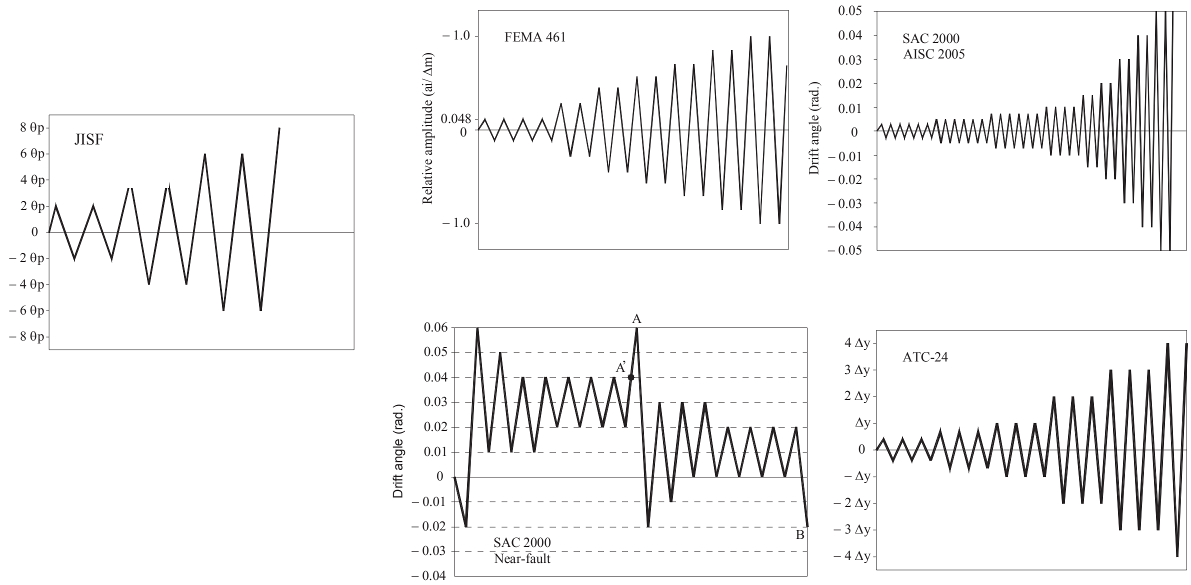


Figure 7. Japanese and American recommended loading protocols

3.2 American Loading Protocols

The deformation controlled loading protocols from FEMA 461, AISC 2005, SAC 2000, as well as ATC-24, which are recommended in the U.S. for steel beam testing, are investigated. These loading protocols are also shown in Figure 7. The descriptions of these loading protocols are as follows:

FEMA 461 (FEMA 2007) :
This protocol was developed originally for testing of drift sensitive nonstructural components, but is applicable in general also to drift sensitive structural components like beams. It used a targeted maximum deformation amplitude Δ_m. Loading starts from $a_1 = 0.048\Delta_m$, with $a_{i+1} = 1.4a_i$. At each amplitude, 2 cycles should be applied. Δ_m : Targeted maximum deformation amplitude, which can be estimated from a monotonic test. A recommend value is 0.03 (in terms of story drift index δ / h).

AISC 2005 (Seismic provision) (AISC 2005):
This loading protocol is recommended by the American Institute of Steel Construction for testing beam-to-column moment connections in special and intermediate moment frames. The cyclic loading protocols are in terms of inter-story drift angle θ:
6 cycles at θ=0.00375rad→6 cycles at θ=0.005rad→6 cycles at θ=0.0075rad→4 cycles at θ=0.01rad→2 cycles at θ=0.015rad→2 cycles at θ=0.02rad→2 cycles at θ=0.03rad→2 cycles at θ=0.04rad→Continue loading at increments of θ=0.01rad, 2 cycles at each step.

SAC 2000 (Krawinkler 2000):
Two kinds of loading protocols are recommended in the SAC 2000 program. First one is the basic loading history for beam-to-column connections in SMRF. The SAC protocol includes more small elastic cycles because of the observed Northridge weld fractures that occurred before yielding occurred (Youssef 1995). The second loading protocol recommended by SAC 2000 is the near-fault loading history.
SAC 2000: Basic loading history: This loading protocol is the same as AISC 2005.

<u>SAC 2000: Near-fault loading history</u>: The cyclic loading protocols are in terms of inter-story drift angle θ.

ATC-24 (Krawinkler 1992):
The ATC-24 was specifically developed for components of steel structures, was one of the first formal protocols developed in the U.S. for seismic performance evaluation of components using a cyclic loading history. This cyclic loading protocol is in terms of beam's elastic deformation Δ_y:

3.3 Beam Performance under Recommended Loading Protocols

The cyclic in-plane analyses of cantilever beam are conducted, with the input beam free-end deformation corresponding to each recommended loading protocols in Japan and the U.S.. In order to compare with the beam performance in the frame, the analytical model of the cantilever beam is the same as the beams in the frame analysis. The JISF and ATC-24 loading protocols are in terms of beam rotations, the beam free-end deformation can be obtained directly by times the beam span. However, the other loading protocols introduced are in terms of story drifts ($\frac{2\delta_H}{Lc+D}$), which have to be converted into the beam rotations (θ_b). Here, the column and panel zone is considered to remain elastic.

The growing processes of the plastic strain ratio at the flange fracture zone are plotted in Figure 8. In this graph, the growing process under SAC-Near-fault loading protocol shows totally different route from that under the other loading protocols. The growing processes under the rest of the loading protocols are similar to each other. Especially for loading protocols SAC 2000 and FEMA 461, almost same growing processes can be seen from the graph.

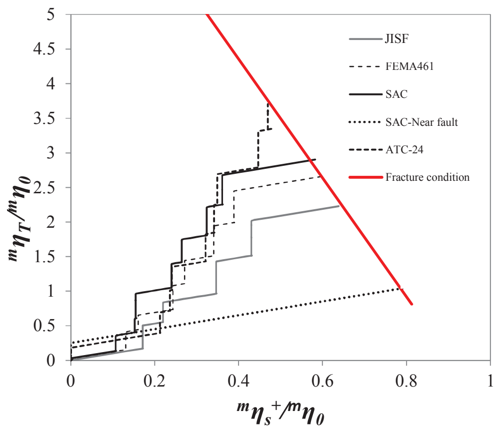


Figure 8. Growing processes of the plastic strain ratio under recommended loading protocols

4. SUGGESTION ON SELECTING LOADING PROTOCOLS IN BEAM TESTING

4.1 Investigation of the Recommended Loading Protocols

In the tests to evaluate the beam's seismic performance, especially plastic deformation capacity under seismic effects, a loading protocol is suitable or not lies on its reproduction of the beam's behavior under (as various as possible) real earthquake ground motions. The seismic behavior of the beam flange under 11 ground motions was obtained in Section 2. The growing processes of the plastic strain ratio at the beam flange fracture zone show distinguished routes in Figure 6. The plastic strain ratio growing processes under 11 ground motions cover a certain area. From Figure 6, the envelope of the area at BSF is obtained. The area covered by the envelope represents the beam's behavior under different types of ground motions. In order to investigate the practicality of the recommended loading protocols, the growing processes of the plastic strain ratio under these recommended loading protocols (Figure 8) are plotted into the envelope (Figure 9).

The results of the JISF, FEMA461, SAC2000, AISC2005, and ATC-24 loading protocols gather in the middle part of the envelope. The result of the SAC-Near-fault loading protocol reaches out to the bottom edge of the envelope. Taking a broad view of the whole graph, there are two obvious parts in the envelope that cannot be cover by the results of the recommended loading protocols, pointed out in the dark blue cycles. The one at the top is where the long-duration ground motions such as Iwaki record lays. The feature of the beam responses in this area is large number cycles of relatively smaller deformation amplitude. The other inadequate part between the SAC-Near-fault protocol and the rest of the loading protocols is the area that the ground motions with the characteristic of large amplitude beam responses lay. The inadequate parts in the envelope should be taken into consideration in choosing the reasonable loading protocols.

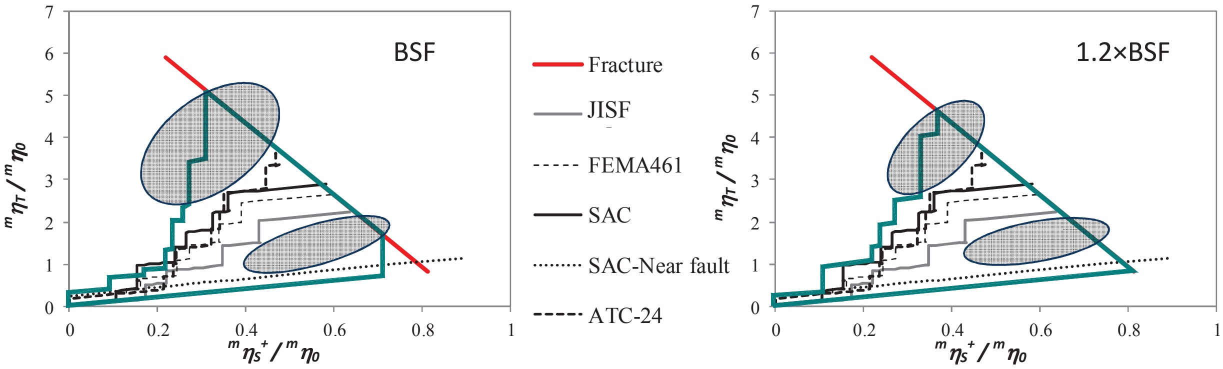


Figure 9. Comparison of the “envelop” and the beam behavior under recommended loading protocols

4.2 Complementary Loading Protocols

To cover the inadequate parts in Figure 9, beam’s performance under three loading protocols shown in Figure 10 was also evaluated. The details of these three loading protocols are as follows:

1. Constant amplitude loading of $\pm 3\,\theta_P$
2. Constant amplitude loading of $\pm 4\,\theta_P$
3. Modi-JISF loading protocol: incremental cyclic loading starting from $\pm 2\,\theta_P$, with intervals of $2\,\theta_P$

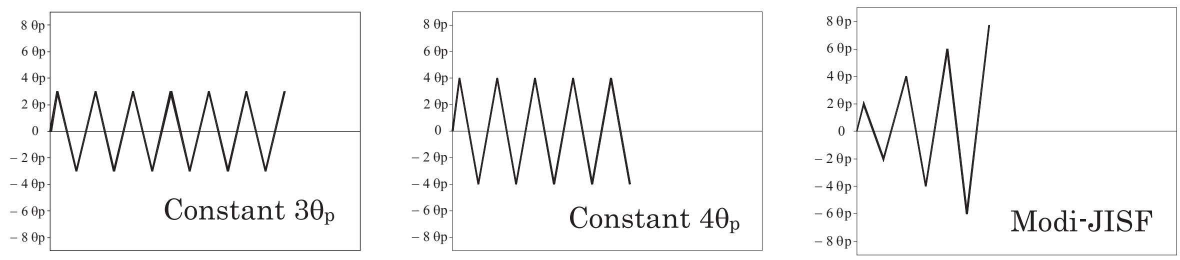


Figure 10. Complementary loading protocols

The growing processes of the plastic strain ratio at the flange fracture zone under the complementary loading protocol are plotted in Figure 11 together with the results of the recommended Japanese and American loading protocols and the envelope under BSF. This graph indicates that beam performance under constant amplitude loading protocols of $\pm 3\,\theta_P$ reproduces the beam performance under long duration ground motion. The Modified JISF protocol fills the blank between the Near-fault earthquake and other recommended loading protocols.

Figure 12 shows the deform performance of the beam component under all loading protocols till fracture. The SAC, FEMA 461, and JISF loading protocols show very similar results, which can reproduce the beam's performance under generic earthquakes. When the amplitude of the loading protocol decreases, the growing processes lean to the upper-left side. The loading protocols in this area reproduce the beam's performance under long duration ground motions. On the other side, when the amplitude increases, the growing processes lean to the lower-right corner, which is the domain of near-fault ground motions.

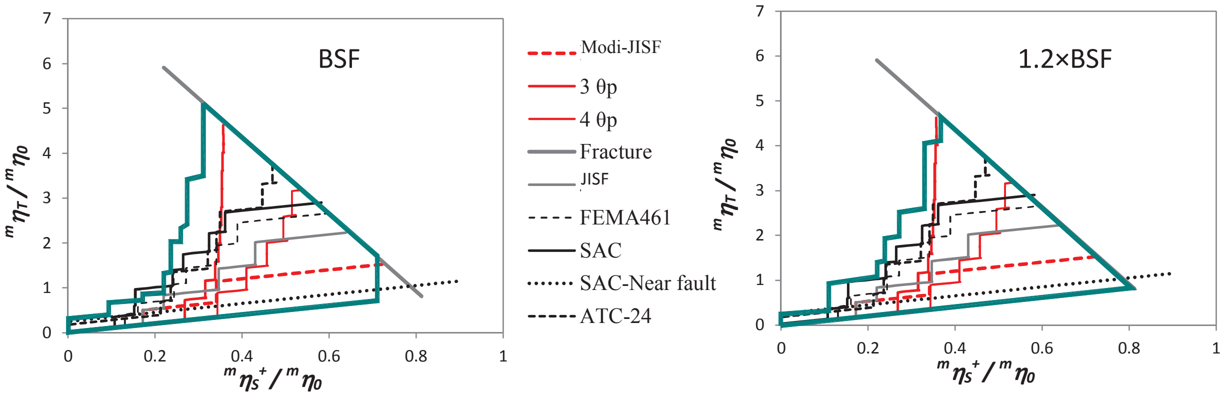


Figure 11. Comparison of the "envelop" and the beam behavior under all loading protocols

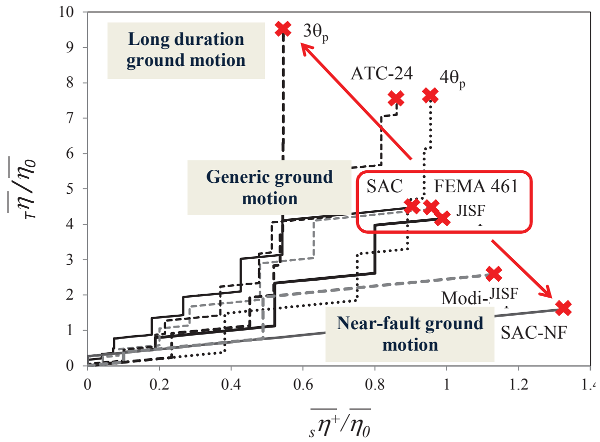


Figure 12. Equivalent cumulative deformation ratio of beams under recommended loading protocols

Based on the above discussion, suggestions are given as follows to the selection of loading protocols in beam tests:

Single specimen testing program

One loading protocol from the SAC 2000/ASIC, FEMA 461, or JISF loading protocols.
*For the beams possibly suffering brittle fracture, SAC 2000/ASIC loading protocol is recommended.

Multiple specimens testing program

Testing program with at least three specimens is recommended.
1) One loading protocol from the SAC 2000/ASIC, FEMA 461, or JISF loading protocol.
*For the beams possibly suffering brittle fracture, SAC 2000/ASIC loading protocol is recommended.
2) One constant amplitude loading protocol with small loading amplitude, for example: $\pm 3\,\theta_P$.
3) Either the monotonic loading protocol or the SAC-Near-fault loading protocol.
*When there is a limitation of the facility, constant amplitude loading protocol with the largest loading amplitude of the facility is recommended.

4. CONCLUSION

This study focuses on the investigation of loading protocols employed in beam testing. Beam seismic performance in a weak-beam moment frame under various earthquakes is obtained through response analysis and in-plane beam analysis. By comparing the beams performance under the recommended Japanese and American loading protocols and that under ground motions, Suggestions were given on the selection of loading protocols in beam tests for the purpose of evaluating the seismic performance of the beam.

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