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# Lateral Force-Resisting Capacities of Reduced Web-Section Beams: FEM Simulations

*Seungpil Kim[1)], Myoungsu Shin[2)], and Mark Aschheim[3)]

*[1), 2)] School of Urban and Environmental Engineering, UNIST, Ulsan 689-798, Korea*
*[3)] Department of Civil Engineering, Santa Clara University, Santa Clara, California, USA*

*[1)]kimsp1205@unist.ac.kr*
*[2)] msshin@unist.ac.kr*

## ABSTRACT

Avoiding fracture in the beam-column connections of steel moment frames is critical to their seismic performance. In the RWS approach, large openings are introduced into the web of the beam, so that the arrangement and configuration of the openings determine the mode of inelastic mechanism that develops within the beam. In this paper, numerical simulation results are discussed for nine RWS specimens that were subjected to lateral loading.

## 1. INTRODUCTION

The unexpected fracture of welded beam-column connections of steel moment frames in the Northridge and Hyogo-Ken Earthquakes in the mid-1990s has motivated the development of methods to improve the performance of the system (FEMA 2000, SAC 2000). Some methods focus on increasing the toughness of the beam-column connections (Chen 1996, Civjan 2000), while other methods aim to limit the intensity of stress at the connections by shifting the location of plastic hinging away from the beam-column welds. Examples of the latter include the use of haunches (Engelhardt 1998, Uang 1996, Uang 1998) and the removal of portions of the beam flange near the connections (known as a “Reduced Beam Section”) (Chi 2002, Jones 2002). These approaches enforce yielding to develop in flexure at critical (weaker) locations away from the beam-column connections.

In the present study, an innovative method of reducing the shear strength of a wide-flange beam is explored aiming at inducing yielding within the beam span due to beam shear. Because steel beams of ordinary dimensions have ample shear strengths compared with the shear demands, relatively large openings must be introduced in the web to generate yielding due to beam shear. This paper presents the results of nonlinear finite element analyses of nine RWS beams subjected to lateral loading, and discusses the lateral force-resisting mechanisms.

## 2. SPECIMEN DESIGN

In this study, nine approximately full-scale beam specimens were simulated subjected to lateral loading. Each frame specimen consisted of a wide-flange beam having a unique reduced-web configuration. Various web opening geometries (Figure 1) were explored to discover inelastic mechanisms that achieve ductile behavior prior to the incident of significant inelastic deformation at the beam-column connections.

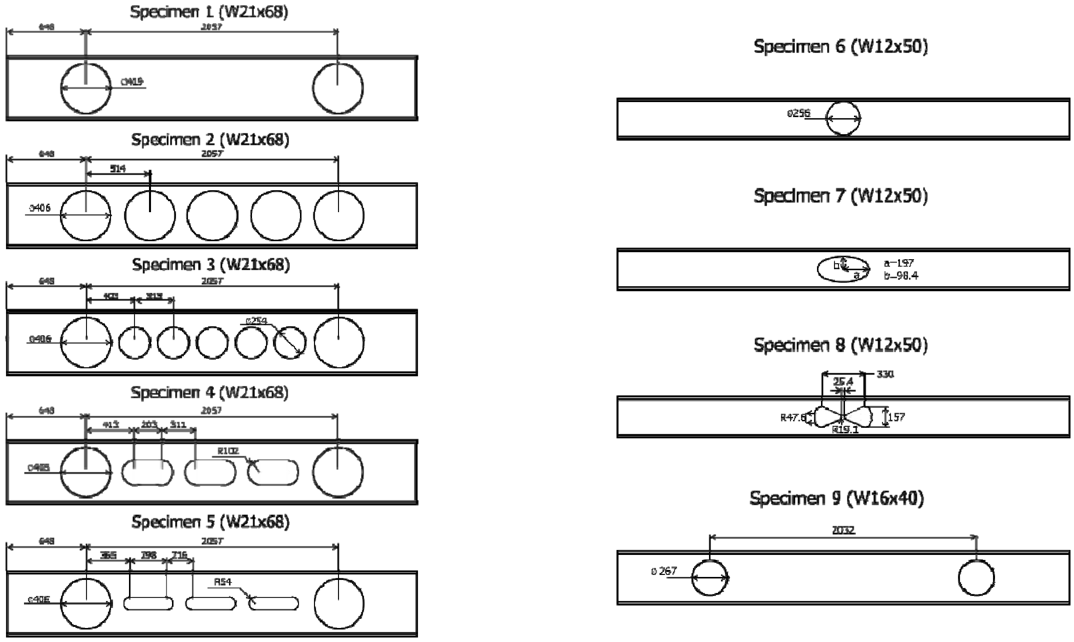
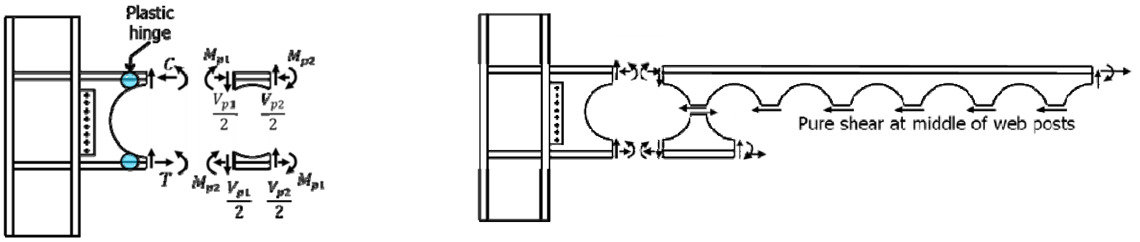


Fig. 1 Specimen geometries (units: mm)

The specimens were designed aiming at identifying primary behavioral characteristics associated with Modes A and B, such as strength, deformation capacity, failure mode, and type and onset of instability. Figure 1 presents web opening geometries in the specimens. The same wide-flange shape W21×68 (Grade 50) was used for the beams in Specimens 1 to 5, so that the effects of web opening geometry would be readily evident. Specimen 1 was designed to investigate the Mode-A mechanism, while Specimens 2 to 5 were designed to investigate the Mode-B mechanism.

For Specimens 6 to 9, the primary design intention was to prevent considerable inelastic behavior at beam-column connections prior to achieving sufficient ductility. Specimens 2 to 5 designed to reduce in the lateral resistance that was attributed to the out-of-plane buckling of web posts. This was likely originated from the kinematics of the Mode-B mechanism that requires the shortening of the web posts. Therefore, Specimens 6 to 9 focused on the Mode-A mechanism with an intention to avoid the loss of strength observed in Specimens 2 to 5. The tested beam was fabricated with W12×50 (Grade 50) in Specimens 6 to 8, and W16×40 (Grade 50) in Specimen 9. The design of Specimen 9 was similar to that of Specimen 1 with two circular web openings near the beam-column connections. Thus, Specimen 9 was expected to undertake a similar inelastic mechanism as Specimen 1.

The web openings were proportioned initially assuming potential inelastic mechanisms on the basis of aforesaid plastic mechanism analyses; the designs were subsequently validated using detailed nonlinear finite element analysis (FEA). For the design of Specimen 1, the free-body diagram in Figure 2-(a) was considered, and for the design of Specimens 2 to 4, the free-body diagram in Figure 2-(b) was considered.



(a) Mode-A (b) Mode-B

Fig. 2 Free-body diagrams for reduced web-section beams in two inelastic mechanisms

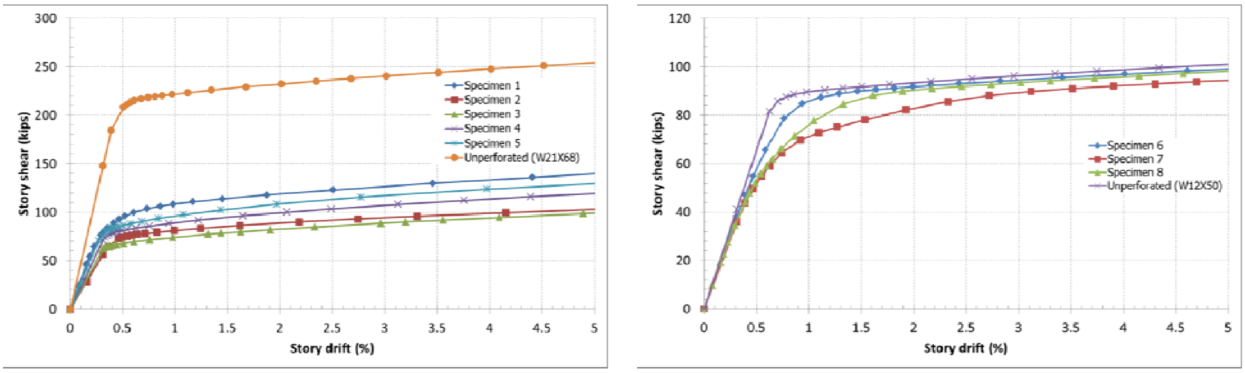
## 3. NONLINEAR FEM RESULTS AND DISCUSSIONS

Nonlinear finite element analyses (FEA) were conducted for the nine specimens as well as control specimens (designated “Unperforated W21×68”, “Unperforated W12×50”, and “Unperforated W16×40”) having the same shape beam with no web openings. These analyses were done using ABAQUS software. The nominal specimen dimensions shown in Figure 1 were considered, and the clear span length was taken as 3350 mm (132 in.). Some simplifying assumptions were made: the bilinear stress-strain relationship of steel was assumed with the material properties in Table 1, and the post-yield (strain-hardening) modulus of 1.38 GPa (200 ksi).

Table 1 Material properties of steel (1 kip = 4.45 kN)

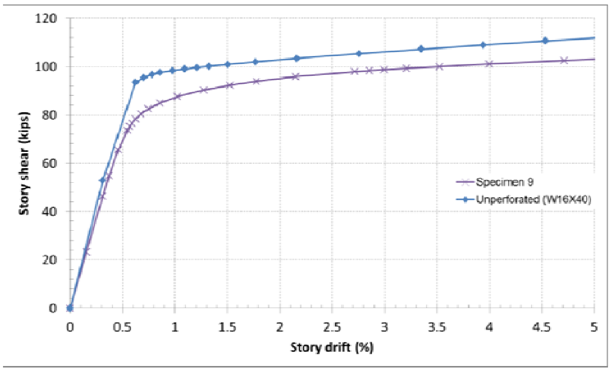
| Specimens | Modulus of elasticity (ksi) | Yield strength (ksi) | Tensile strength (ksi) |
|---|---|---|---|
| 1, 2, and 3 | 32,500 | 60 | 77 |
| 4 and 5 | 32,500 | 57.5 | 76 |
| 6, 7 and 8 | 29,000 | 54 | 75 |
| 9 | 29,000 | 59 | 79 |

To simulate only the beam of Figure 1 in the numerical model, one end of the beam was fully restrained against both translation and rotation, while the other end was released for translation only in the direction transverse to the longitudinal axis of the beam. Then, loading was applied along the released direction at this end. Since there was no attempt to model instability (e.g., buckling), no initial out-of-straightness was modeled.



(a) Specimens 1 to 5 (W21X68)

(b) Specimens 6 to 8 (W12X50)

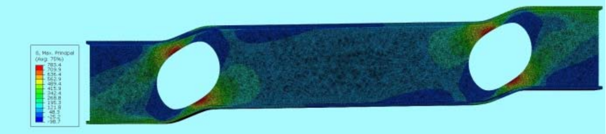


(c) Specimen 9 (W16X40)

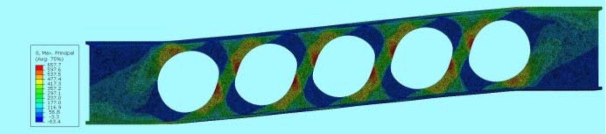
Fig. 3 Nonlinear finite element analysis results: (a) Specimens 1 to 5, (b) 6 to 8, and (c) 9 (1 kip = 4.45 kN)

Figure 3 plots the computed story shear-story drift responses of the specimens; based on the geometry of the loading frame in Figure 1, the story shear is taken as 1.43 times the beam shear, and the story drift is taken as the beam chord rotation divided by 1.34, in which the chord rotation is the transverse displacement divided by the clear span length of the beam.

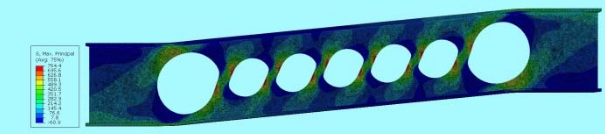
Specimen 1



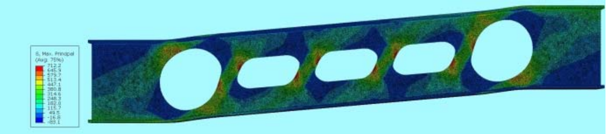
Specimen 2



Specimen 3

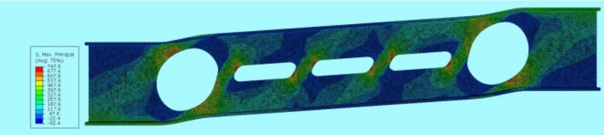


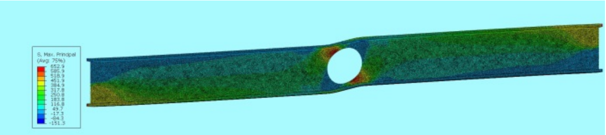
Specimen 4



Specimen 5

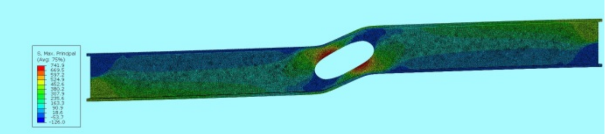
Specimen 6

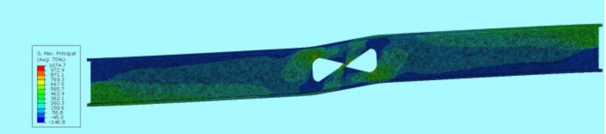




Specimen 7

Specimen 8





Specimen 9

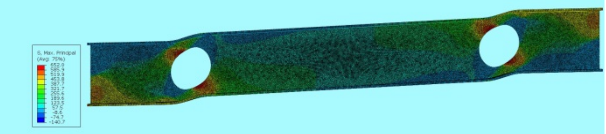


Fig. 4 Maximum principal stress distribution at 5% beam chord rotation (units: MPa)

According to the FEA results, yielding initially occurs in the webs around the edges of the openings in Specimen 1, while it happens in the web posts in Specimens 2 to 5. As shown in Figure 4, the inelastic mechanism of Specimen 1 is governed by the development of plastic hinges in the T-beams above and below each web opening (Mode-A); each T-beam deforms in a double curvature. In contrast, the overall behaviors of Specimens 2 to 5 are considered each as a hybrid between a diagonal truss consisting of tension ties and compression struts acting through the web posts, and a Vierendeel truss (Fu 2004) inducing bending of the T-beams above and below the openings (Mode-B).

Of Specimens 1 to 5, Specimen 1 in the Mode-A mechanism shows the highest yield strength, while Specimen 3 with the most slender web posts shows the lowest yield strength. Among the specimens with five openings at the same spacing, the specimen having the more slender web posts exhibits the smaller yield strength. However, out-of-plane buckling of the web posts and fracture of the web was not modeled and could substantially affect the strengths of the specimens in the tests.

According to the analyses, Specimens 6, 7, 8, and 9 go through similar mechanisms (Mode-A) and damage sequences: initial yielding around the web opening(s) followed by plastic hinging in the T-beams above and below the opening(s), as well as yielding at the beam-column connections (Figure 4). However, out-of-plane buckling or fracture of the web was not modeled and could substantially reduce the strengths of the specimens in the tests. Unlike Specimens 1 to 5, Specimens 6 to 9 experience slight yielding at the connections.

## ACKNOWLEDGEMENT

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