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리브로 보강된 내진 철골 모멘트 접합부의 응력전달 메커니즘

Force Transfer Mechanism of Seismic Steel Moment Connections Reinforced with Ribs

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ABATRACT

본 연구에서는 리브로 보강된 내진 철골 모멘트 접합부의 응력전달 메커니즘을 검토하였다. 리브보강 접합부의 응력전달 메커니즘은 고전 휨이론에 의한 예측과 전혀 다르다. 일반적으로 구조기술자가 리브를 사용할 경우 단면이차모멘트의 증가에 따른 휨응력의 감소효과를 기대하는 것이 보통이다. 그러나 리브는 구조기술자들이 통상 가정하는 휨응력 전달요소라기 보다는 리브 구배방향의 스트럿 요소로 기능하여 휨응력 외에도 전단응력을 전달한다. 리브를 스트럿 요소로 파악할 때 응력전달 메커니즘을 올바로 파악할 수 있으며 이를 기초로 합리적 설계법의 정립이 가능하다

1. INTRODUCTION

The 1994 Northridge, California earthquake caused widespread brittle fracture in connections of steel moment-resisting frames. A variety of improved moment connection details were proposed after the earthquake. Two key strategies to circumvent the problems associated with the pre-Northridge connection include strengthening the connection or weakening the beams that frame into the connection [Bruneau-Uang-Whittaker 1998]. The aim is to shift the plastic hinging away from the face of the column, thus reducing the possibility of brittle failure conditions. Fig. 1 shows examples of moment connections per strengthening strategies. Typical configurations of the rib-reinforced moment connections are shown in Fig. 1(b). The rib connections have been demonstrated to perform well in the full-scale test conducted by Zekioglu et al. (1997). Fig. 2 shows one of the connection

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details from their project-specific testing (specimen COH-1). In this case, rib reinforcement was used to supplement the taper-cut reduced beam section (RBS), i.e., to further limit the stress in the beam flange welds and to provide increased redundancy for the connection. Rib reinforcement may be also used to address the situation where the frame design requires an excessive RBS (greater than 50 percent of the beam flange) due to short spans, or larger beam depths.

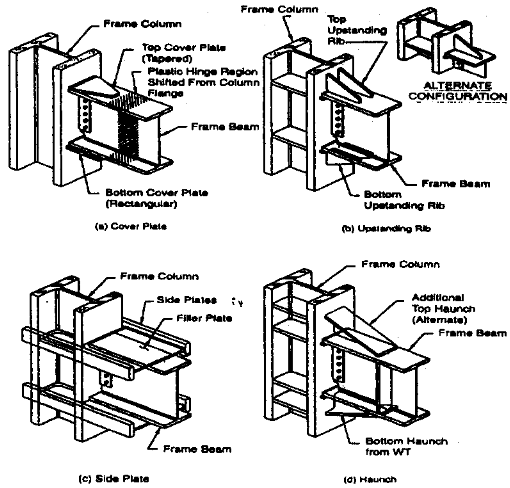


Fig. 1 Post-Northridge Connections per Strengthening Strategies [Ref. 1]

However, a design procedure for the rib connection has not been established yet. Engineers often use rib plates to enhance the seismic performance of welded steel moment connections, thinking that the moment of inertia is increased near the face of the column so that the tensile stress in the groove weld is reduced. Previous studies have indicated that the classical beam theory cannot provide reliable force transfer predictions in the steel moment connections with welded haunch (Lee-Uang 1997, Lee-Uang 2000a-b, Yu-Uang-Gross 2000). Especially it was shown in Lee and Uang's studies that an inclined strip in the web of the straight haunch acts as a strut rather than following the beam theory. Lee and Uang viewed the web of straight haunch as a vertical rib plate and the haunch flange as a stability element. It was speculated that there exists close link between the rib and the straight haunch.

In this study, employing the beam theory for the design of rib-reinforced steel moment connections is brought into question first. Numerical investigations of the strut action in rib are then described to establish a simplified analytical modeling as well as a practical design procedure.

2. NUMERICAL SIMULATION AND INTERNAL STRESS DISTRIBUTION

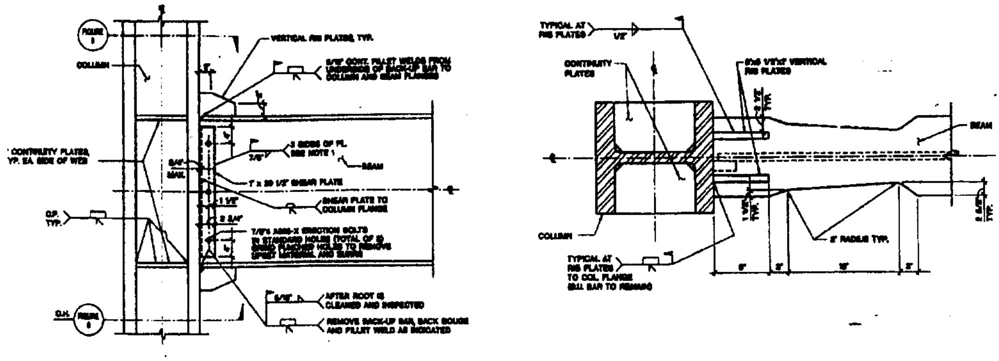


Fig. 2 Rib-Reinforced Connection Details: Specimen COH-1

To gain insight into the behavior of the rib connection, the test specimen COH-1 was modeled and analyzed using the general-purpose finite element analysis program ABAQUS (HKS 1998). Fig. 3 shows the test setup. The specimen consisted of W27X178 beam (W706X792) and W14X455 column (W483X2025). The test specimen COH-1 had a rib length of 229 mm (9 in), a rib height of 165 mm (6.5 in), and a rib thickness of 25 mm (1 in). Both the flanges and web of the beam and column were modeled with the 8-node continuum element (element type C3D8 in ABAQUS). The beam web was directly connected to the column flange in the model. Fig. 4 shows the finite element mesh in the connection region. Steel material properties obtained from tensile coupon tests were used. Material nonlinearity with the von Mises yielding criterion was considered in the analysis. The analytically predicted load versus beam tip deflection relationship was correlated with the response envelope of the test result in Fig. 5. The correlation was reasonable. The finite element model was then used to investigate the stress distribution in the connection region.

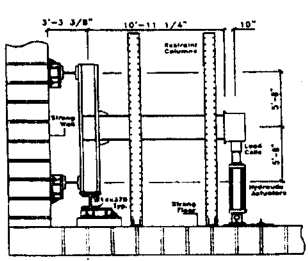


Fig. 3 Test Setup for the Specimen COH-1

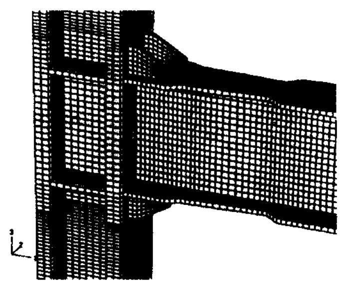


Fig. 4 Finite Element Mesh for the Specimen COH-1

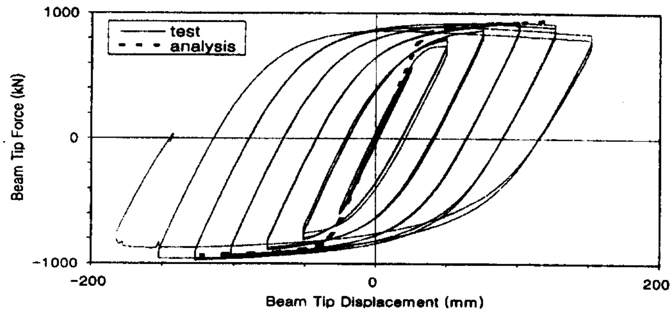


Fig. 5 Correlation of Analytical and Experimental Global Responses

Plastic hinging of the beam is often assumed to occur at the rib tip. However it is difficult to justify this assumption due to light reinforcement nature of the rib. Some positive measures such as the RBS is desirable to maintain the rib region truly elastic by pushing the plastic hinging of the beam away from the rib region. Typical beam span with rib connection assumed in this study is shown in Fig. 6, where the radius-cut RBS is introduced to effectively confine the plastic hinging of the beam outside the rib region. Since the rib region is expected to remain essentially elastic under this scheme, an elastic analysis with a 712 kN (160 kips) load applied at the beam tip was conducted to study the force transfer mechanism of the connection.

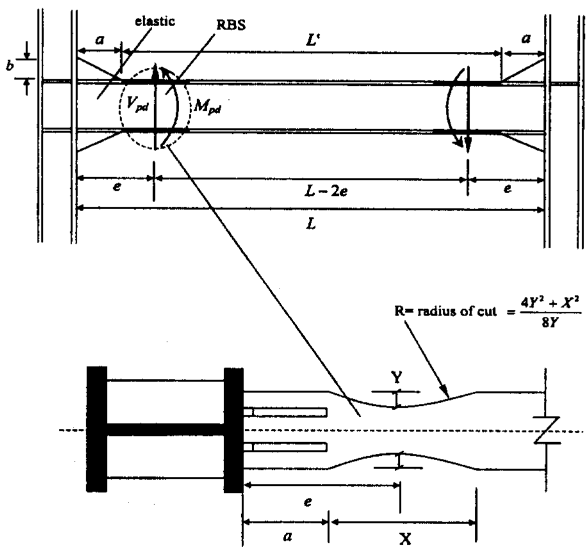


Fig. 6 Typical Beam Span with Rib Connection Supplemented by Radius-Cut RBS

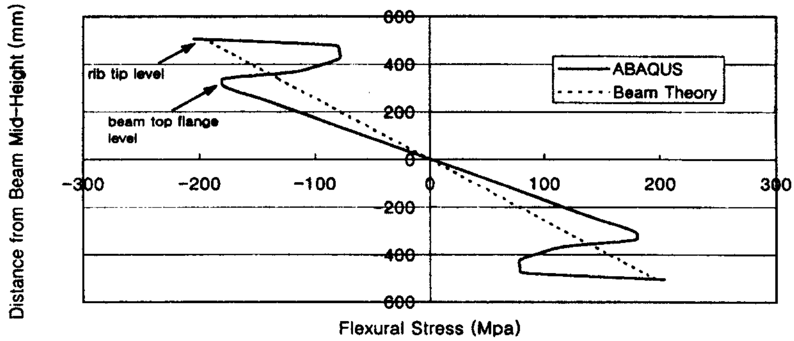


Fig. 7 Comparison of Flexural Stress Profiles along Beam Depth (Specimen COH-1)

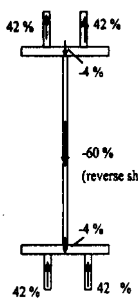


Fig. 8 Shear Transfer at the Column Face (specimen COH-1)

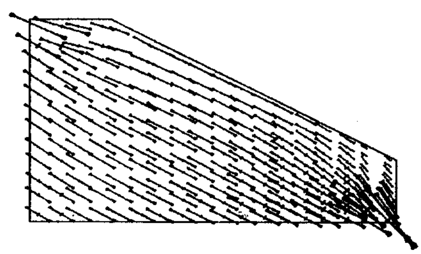


Fig. 9 Principal Stress Distribution in the Rib

Based on the analysis results, the flexural stress profile at the column face is presented in Fig. 7. The flexural stress profile from the beam theory by treating the beam and ribs as an integral section is also presented. It is evident from this figure that the force transfer mechanism in the rib connection cannot be reliably predicted by the beam theory. Note that the beam theory significantly underestimates the stress at the beam flanges, i.e., the stress in the beam flange groove welds. Fig. 8 shows the percentage of the beam shear transferred by each element at the face of the column. The ribs transfer 168 % of the beam shear applied and produces reverse shear in the beam web. Again this phenomenon cannot be explained by the beam theory. The principal stress distribution in the rib in Fig. 9 suggests clear diagonal strut action in the rib. This strut action of the rib can be used to explain the reverse shear phenomenon noted above.

Analyses were performed to investigate the stress distribution at the beam-rib interface. In addition to analyzing the test specimen COH-1 with a rib length, *a*, of 229 mm (9 in), a rib height, *b*, of 165 mm (6.5 in), and a rib thickness, *t*, of 25 mm (in), additional cases were also included in the parametric study by varying the rib slope and the rib thickness within some practical ranges. Similar parametric study was also conducted for the single rib configuration (see Fig. 10a).

The normal and shear stress distributions along the beam-rib interface are presented in Fig. 11, where the stress profile of each case has been normalized by the maximum stress

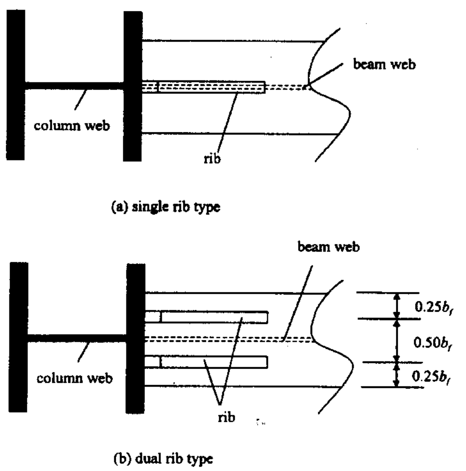


Fig. 10 Two Types of Rib Configuration

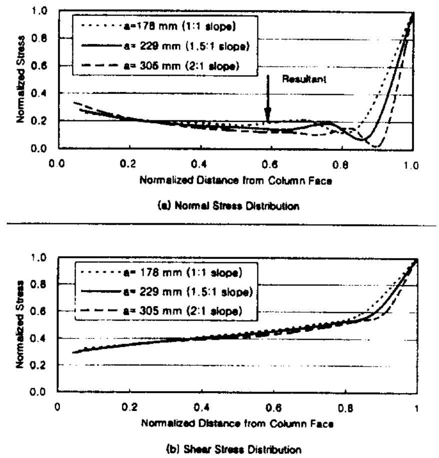
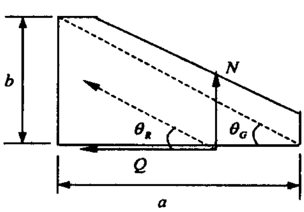


Fig. 11 Typical Normal and Shear Stress Distributions along Beam-Rib

and the distance has been normalized by the rib length. Similar distributions were also obtained when the rib thickness was varied (results not shown). Fig. 11(a) shows that the resultant normal force, N, is located approximately at a distance of $0.60a$ from the face of the column. Stress concentration at the rib tip is also evident. Fig. 11(b) shows that the shear stress profile is insensitive to the variation of rib length. The total shear force at the beam-rib interface is defined as Q. The resultant from force components N and Q, and the associated angle are listed in Table 1.

Table 1 Comparison of Rib Diagonal and Resultant Angles



$\theta_G = \tan^{-1}(b/a)$ (degree)	$\theta_R = \tan^{-1}(N/Q)$ (degree)	
	single rib type	dual rib type
42.9	39.4	41.8
35.8	35.2	36.1
28.4	30.9	32.9

(a) single rib type (b) dual rib type

Fig. 12 Comparison of Deformed Shapes

As was suggested from the principal stress plot in Fig. 9, the resultant angle of Q and N reasonably matches the rib diagonal angle. Fig. 12 compares the deformed shapes of the single and dual rib configurations. It is noted that the load path of the single rib configuration is more direct because all of the beam web, rib and column web plates exist in co-plane and it does not accompany the beam flange bending which is unavoidable in the dual rib configuration. Accordingly it is expected that the load transferred by one rib in the dual rib configuration will be smaller than that by the rib in the single rib configuration having the same rib thickness. To confirm this expectation, Q and N values from the finite element analysis for both configurations are compared in Table 2. It is observed that the load transfer of the single rib configuration is about two times that of one rib in the dual rib configuration. Additional analyses also confirmed this observation. This information is important in designing the connection with the dual rib configuration.

Table 2 Comparison of Q and N values in Single and Dual Rib Configurations

	single rib		dual rib	
	Q	N	Q*	N*
a= 178 mm (1:1 slope)	1.0	1.0	0.99**	0.98
a= 229 mm (1.5:1 slope)	1.0	1.0	1.09	1.10
a= 305 mm (2:1 slope)	1.0	1.0	1.15	1.15

*sum of two ribs

**relative values

Based on the above observations from the finite element analysis, An equivalent strut model as well as a step-by-step design procedure which considers the strut action in the rib have been proposed (Lee et. al, 2001). Fig. 13 shows the basic concept of the equivalent strut model proposed. Detailed description for the model is omitted here due to space limitations.

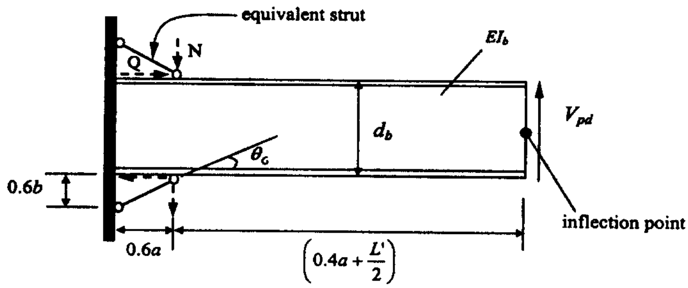


Figure 13 Equivalent Strut Model

3. CONCLUSIONS

Main conclusions on the force transfer mechanism of seismic steel moment connections reinforced with ribs are summarized as follows:

The rib drastically changes the force transfer mechanism that cannot be predicted reliably by the classical beam theory. The flexural stress prediction from the beam theory by treating the beam and ribs as an integral section significantly underestimates the stress in the beam flange groove welds. Diagonal strip in the rib acts as a strut and this strut action tends to produce reverse shear in the beam web. Idealizing the rib as a strut, it is possible to develop an equivalent strut model that could be used as the basis of a practical design procedure.

4. ACKNOWLEDGMENTS

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