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SEISMIC DESIGN PROCEDURE AND DETAILING OF NEW REDUCED BEAM SECTION MOMENT CONNECTION WITH CORRUGATED WEB IN BEAM PLASTIC HINGE ZONE

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Key Words: RBS moment resisting connection, steel structures, seismic ductility, plastic hinge, steel corrugated plates, finite element analysis.

ABSTRACT Reduced beam section (RBS) moment resisting connections have been known as a famous steel moment connections for steel structures, because of their economical advantages and seismic ductility. Improvement of seismic ductility and decreasing the stress concentration in the end of the beams, that connect to the column with RBS connection, cause to use of these connections increase after the 1994 Northridge earthquake. In the common RBS connection, plastic section modulus of beam decreases with diminishing of beam flange width in the plastic hinge zone, and forming of plastic hinge transfer to the reduced region from the column face. Using of steel corrugated plates in the beam web is a manner of section weakening in the beam plastic hinge zone. In this method the beam web is omitted in the plastic hinge limit and corrugated plates are placed in this limit, substitute of beam flat web. Corrugated plates because of their accordion effect don't have bending rigidity and they don't participate in the bending load carrying. Then using of these plates in the plastic hinge region reduces the beam plastic section modulus and plastic hinge is formed in corrugated region. This proposed RBS connection, in addition to providing the requirement of reduced section, with increasing the beam out of plane stiffness in the plastic hinge zone because of corrugated plates shape, prevents any buckling modes in this region. In this paper after presentation of new RBS connection with corrugated plates in the beam plastic hinge zone, seismic design procedure of this connection is presented with using of finite element analysis and notice to code limitations about design methods, construction and installation of RBS connections.

INTRODUCTION

Seismic loading is one of the most important factor in the buildings and any other structure which is resistant towards earthquake. The improvement of building technology has made it feasible to utilize new materials and techniques in the aforementioned structures. Steel is one of the appropriate materials for designing buildings which resistant to gravity and earthquake loads. Special moment-resisting frame system is one of common systems that are used in the design of steel structures. Post-Northridge earthquake observations made upon the steel structures to explore the ductile and safe behavior of the steel moment-resisting frame connections brought about some modifications in the design methods, concepts, construction, installation and the quality control of the structures. In fact the Northridge earthquake in 1994 is a turning point in the design of the seismic steel structures especially the steel moment-resisting frame connections. RBS connections which are also known as the dog bone connections were presented for the first time in USA in 1992. This connection was developed after the Northridge earthquake in 1994 (Engelhardt, 2000). Improvement of seismic ductility and decreasing the stress concentration in the end of the beams, that connect to the column with RBS connection, cause to use of these connections increase after the 1994 Northridge earthquake. Since the RBS beams are reduced in the plastic hinge the aforesaid reduction causes the dwindling of the plastic section module of reduced section and diminishes the seismic demand exerted upon the connection. In the ordinary RBS connection, reduction of the section plastic modules is performed through the weakening of the flanges in the regions where plastic hinge are formed and the web of beam is retained unchanged in reduced section; they have local problems such as lateral-torsional buckling, local buckling of web and flange in the plastic hinge region, formation of fragile cracks before yielding in the section, intricacy of designing and detailing in order to avoiding the stress concentration effects, construction and installation problems specially in circular cut of common RBS connections, and the exclusive utilization of these techniques in the moment resistant structures and etc (Iwankiw,2004).

In this investigation a new alternative of RBS connection, that has been utilized corrugated plates in the web of beam within the plastic hinge region, is persented; therefore we reach a suitable reduced section in the plastic hinge zone of beam in comparison with common RBS connection. Using of steel corrugated plates in the beam web is a manner of section weakening in the beam plastic hinge zone. In this method the beam web is omitted in the plastic hinge limit and corrugated plates are placed in this limit, substitute of beam flat web. Corrugated plates because of their accordion effect don't have bending rigidity and they don't participate in the bending load carrying. Then using of these plates in the plastic hinge zone reduces the beam plastic section modulus and plastic hinge is formed in corrugated region. Proposed connection provide the requirement of a RBS connection, besides with increasing the beam out of plane stiffness in the plastic hinge zone because of corrugated plates shape, prevents any buckling modes in this region. Figure-1 illustrates a sample of proposed RBS connection.

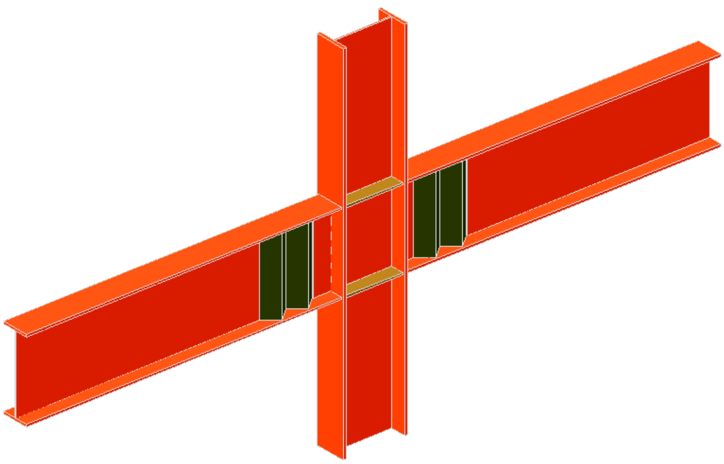

Figure-1. New RBS connection with two box cells made from corrugated plates

ADVANTAGES OF USING THE CORRUGATED PLATES IN THE PLASTIC HINGE ZONE OF THE STEEL MOMENT FRAME BEAMS

The features of using the corrugated plates in the plastic hinge zone of the beams are summarily as follows:

1. The reduced section in the plastic hinge zone is an ideal one, because the flexural capacity of beams in the hinge zone is equal to the plastic moment of the flanges and the web will only participate to sustain the shear stress (Chan,2004), (Elgaaly,1992).

2. The geometric shape of the corrugated plates causes the increase the beam out of plane stiffness and they will be resistant towards the lateral-tortional buckling modes without requires to any stiffness (Chan, 2004).

3. The local buckling of components in the plastic hinge zone is precluded due to the reduction of width to the flange thickness ratio in this region (Goudarzi-Khoigani, 2006).

4. If the web is corrugated, the axial stiffness will diminish, hence the axial forces exerted in the web due to the bending will dwindle and the web won't be very sensitive to the buckling and the construction effects will not have large impacts upon axial stresses.

6. RBS connections with corrugated plates are not a complicated procedure like reinforced moment connections and do not require high costs and plenty of materials.

8. The expenditures of the reinforced connections are exorbitant especially if deep beams are used in tall buildings and RBS connection is a more appropriate option for ductile moment connection in deep beams. It is less costly and it exerts less seismic demand upon the connection joint (Bungle, 1997).

9. Attention to one of the dominant criteria in the design of the special moment resisting frame systems (SMF) which is the main feature in high rise structures is the control of the drift or the relative displacement of the frame stories. In case deep beams with RBS connections are used in these structures the quandary of the structures drift will be solved and the expenses of the design of the reinforced connections will be diminished.

LITERATURE REVIEW

The aforementioned features have instituted the researchers to heed the performance and behavior of the corrugated web beams and RBS connections.

A research team by the name of BTP made researches upon the corrugated web beams in France. Cheyrezy & Comboult (1990), Yoda et all (1994), Lebon (1998), Cafobla & Johnson (1997), Loov & El-Metvolly (1998), made extensive studies upon the various features of the aforementioned beams but Elgaaly published a comprehensive report on these beams in 1997(Elgaaly,1997). Elgaaly et al (2006) made some investigations upon the corrugated web bridge beams. Khalid et al (2004) probed the bending behavior of the corrugated web beams (Chan, 2004).

A collection bearing the experiments implemented upon RBS connections with circular radius cut up to 1999 has been published by Engelhardt et al (1999). SAC database presented a vast array of experimentations in 1999 which comprised 95 RBS connections experimented before. Engelhardt et al (2000), Yu et al (2000), Gilton et al (2000) experimented upon 70 specimens of connections. Jones (2000), Deierlein et al (1999) examined the finite element researches (Ricles, 2004).

Design Procedure Of Proposed Connection

In regard to design codes and finite element analysis results, designing and detailing of proposed moment connection include the bellow steps:

Step 1: Determining the location of beam reduced section which corrugated plates must place in this location, FEMA-350 recommendation was utilized to guess this distance (FEMA 350, 2000).

$$a \cong (0.5 - 0.75) b_f \tag{1}$$

where a is the distance between column face to beginning of beam web cutting location, and b_f is the beam flange width as depicted in Figure-2.

Step 2: Determining the length of beam reduced section or the length of beam web which must be cut.

Because of using the corrugated box with equal side for constructing the beam corrugated web in the plastic hinge zone, considering the length for installing the box from each side of beam flange equal to $0.1b_f$ and FEMA-350 recommendation, length of beam reduced section was limited to following range(FEMA 350, 2000).

$$b \cong Min((0.65-0.85)d_b, 2\times 0.8b_f) \quad (2)$$

where b is the length of beam web cutting as depicted in Figure-2, and d_b is the beam depth.

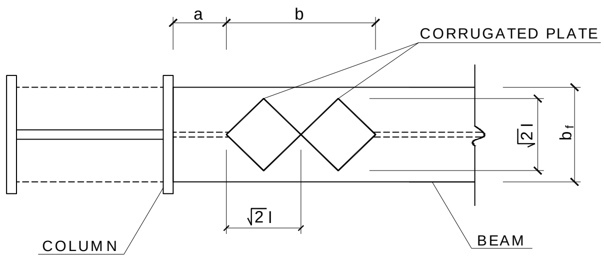

Figure-2. New RBS connection detailing specifications

Step 3: Determining the number of corrugated plate box, that can place in the cutting length of the beam web.

In regard to Step 2 explanation and the length of beam web cutting, the following relationship represent the minimum and maximum number of corrugated box that can place in the cutting length of the beam web.

$$n_{min} = \frac{b_{min}}{b_f - 2\times 0.1b_f} = \frac{0.65d_b}{0.8b_f} = 0.81\frac{d_b}{b_f} \quad (3)$$

$$n_{max} = \frac{b_{max}}{b_f - 2\times 0.1b_f} = \frac{0.85d_b}{0.8b_f} = 1.06\frac{d_b}{b_f} \quad (4)$$

Where n is the number of corrugated box.

Step4: Determining the corrugated box side which is used in the plastic hinge zone

$$l = \frac{(b/2)}{\sqrt{2}} = 0.35\ b \quad (5)$$

where l is the length of the box side.

According to advantages of using corrugated plates in the plastic hinge zone, the total thickness of box can be thinner than beam web thickness.

Step 5: Determining the section plastic modulus of beam reduced section at the location of the plastic hinge.

$$Z_{RBS} = Z_{flange} = b_f \times t_f \times (d_b - t_f) \tag{6}$$

where t_f is the beam flange thickness.

Step 6: Determining the probable peak plastic hinge moment of beam in reduced section (plastic moment originating from the formation of the plastic hinge in the beam).

$$\mathrm{M_{pr}} = \mathrm{C_{pr}} .\mathrm{R_y} .\mathrm{Z}_{RBS} .\mathrm{F}_{yf} \tag{7}$$

where C_{pr} is a factor to account for the peak connection strength, including strain hardening, local restraint, additional reinforcement, and other connection conditions; R_y is a coefficient which is applicable to the beam or girder material, obtained from the AISC Seismic Provisions (AISC, 2005); F_{yf} is the yield stress of beam flange.

Step 7: Determining the moment at the column face.

$$\mathrm{M_f} = \mathrm{M_{pr}} + \mathrm{V_p}(\mathrm{a} + \frac{b}{2}) \tag{8}$$

where V_p is the shear force in the beam reduced section with accounting the lateral and gravitational force.

Step 8: Control of flexural moment at the column face.

$$\mathrm{M}_f < \mathrm{C_{pr}} .\mathrm{R_y} .\mathrm{Z}_b .\mathrm{F}_{yb} \tag{9}$$

where Z_b is the section plastic modulus of beam at the column face; and F_{yb} is the yield stress of beam.

Step 9: Control of beam shear.

$$V_p = \frac{2M_{pr}}{L'} + V_g < \mathrm{F}_{yw} .d_b .t_w \tag{10}$$

where L' is the distance between two plastic hinge of two extremities of beam; V_g is shear force due to gravitational load; F_{yb} is the yield stress of beam web; t_w is beam web thickness.

Step 10: Control of Strong Column-Weak Beam (SCWB); control of panel zone and designing of shear connection for beam accomplishes in regard to steel structures design codes.

THEORY and METHOD

For seismic evaluation of new RBS connection, verifying the seismic design procedure and investigating of design limitation, finite element analysis was implemented using the non-linear finite element analysis program ABAQUS. Aforementioned procedure for new connection is evaluated with using of finite element analysis results and notice to code design limitations (AISC,2005),(FEMA 350,2000).

The finite element model was used to perform a nonlinear inelastic deformation analysis. Quadrilateral 4-node general shell elements (S4) were used for the web and flanges, the nonlinear behavior can be regarded for these elements. To facilitate the geometric modeling, the longitudinal and inclined folds were assumed to intersect without a transition region. The number and size of elements have been considered in a way that the converged solution and the geometric shape of the elements are regular. The weld of connection of the beam flange to the column and the connection of the continuity plates to the column flange are groove weld and the weld of connection of the doublers plates to the column is fillet weld which these welds have not been modeled. The geometry of chosen subassembly for finite element studies is illustrated in Figure-3. This subassembly based on the proposed subassembly by the AISC (AISC, 2005); the location and the type of the subassembly supports and boundary conditions are tabulated in Table-1. The elastic modules, E, was taken equal to 200,000 MPa and Poisson's ratio, v, was taken as 0.3. For the nonlinear inelastic analysis, a kinematic hardening stress versus strain curve, with yield strength of 360 MPa, and ultimate strength of 460 MPa, was used in the models.

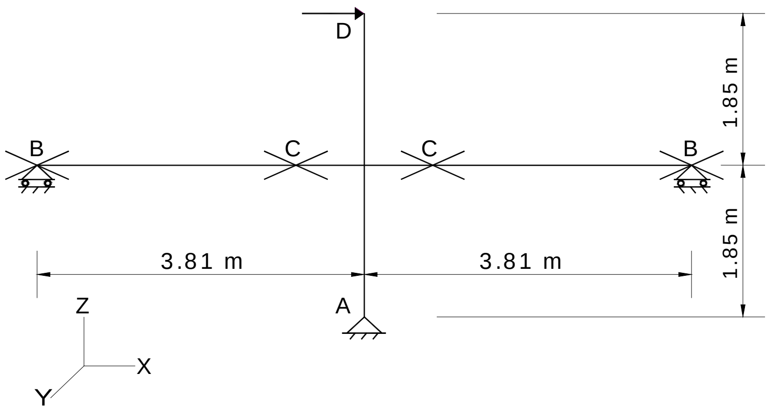

Figure-3. Geometry of subassembly

Table-1. Boundary conditions of finite element model

Point	Translation DOF			Rotation DOF		
	δ_x	δ_y	δ_z	θ_x	θ_y	θ_z
A	R*	R	R	F**	F	F
B	F	R	R	F	F	F
C***	F	R	R	F	F	F
D	DC****	R	F	F	F	F

*Node is restrained, **Node is free, ***Plastic hinge location of beam, ****Node is constrained to displace constantly.

The beam and column section has been fixed in the finite element study, W shape section ($W36 \times 150$) was chosen for beam section and W shape section ($W27 \times 194$) was chosen for column section. The beam and column were pre-selected so that they could satisfy Strong Column-Weak Beam limitation. The specimen was detailed using the above design procedure and finite element analysis results. The calculated doublers plate thickness in each side of column web is equal to 1.2 cm in model; also the continuity plate's thickness in model is equal to beam flange thickness. According to Figure-3 the value of "a" and "b" equal to 20 cm and 50 cm respectively, in regard to the length of "b", obtained "n" (number of corrugated box) for the specimen is equal to 2. All of the design procedure steps were checked for this specimen. The meshing model of the proposed connection with corrugated cells is illustrated in Figure-4. Finite element analysis of designed connection show that plastic hinge concentrate in the theorical plastic hinge location of beam which beam web was omitted and corrugated plates were placed in this distance within the plastic hinge location; The von mises stress contour in the 4% story drift for proposed RBS connection has been illustrated in Figure-5, plastification zone has been placed in the beam flange along the corrugated plates; So the aforesaid design procedure and used steel design codes for designing and detailing of proposed RBS connection satisfy requirements of a rigid connection in a SMF system. Basically "a" is preferred to remain nominally elastic for the ductile RBS. The FEMA-350 suggested range for "a" accomplishes a balance between internalizing unconstrained yielding within the main member while still remaining adjacent to the maximum bending moment demand.

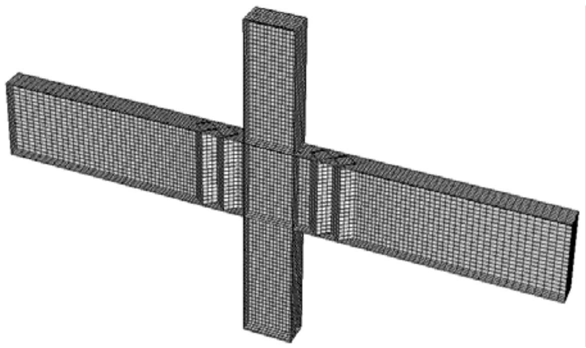

Figure-4. Finite element model of proposed RBS connection

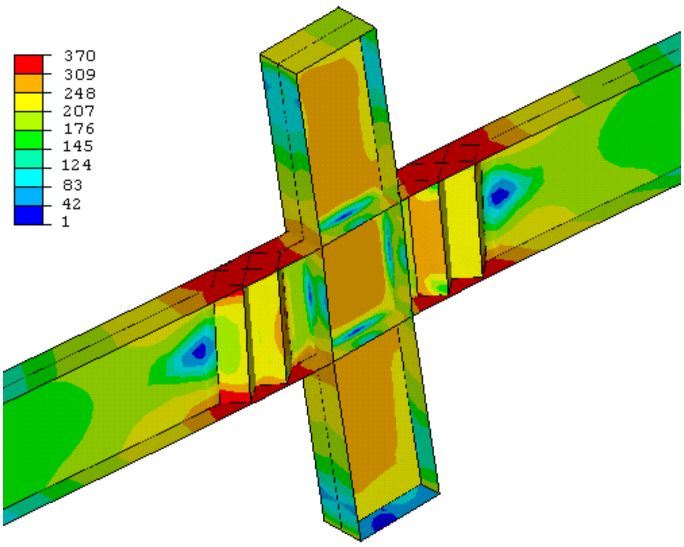

Figure-5. Von mises stress contour at 4% story drift for proposed RBS connection (MPa)

CONCLUSIONS

The main conclusions that can be drawn from this research include:

1. The results of finite element analysis indicate formation of plastic hinge zone in the beam reduced section along the corrugated plate's location away from the beam-to-column interface, and satisfy the FEMA-350 and AISC requirements about location and length of beam reduced section, that designing is accomplished in regard to these recommendations. FEMA-350 and AISC requirements is suitable for proposed RBS connection and satisfied the requirements of new RBS connection as a rigid connection of steel moment frame about transferring the plastification zone within the beam and minimizing the bending moment demand on beam to column connection for designing of connection. The proposed seismic design procedure for new RBS connection with corrugated plates in plastic hinge zone, cover all limitation and requirement of reduced beam connection and steel moment frames with reduced beam sections, and also the proposed seismic design procedure verify the codes recommendations about RBS connection design.

2. The Number of corrugated plates, which is placed in the beam web within plastic hinge zone, depends on beam depth and beam flange width; so detailing of connection which is used more corrugated box in it, will be similar to aforesaid procedure.

3. Detailing, construction and installation procedure of new RBS connection in comparison to common RBS connection is very simple and flexible to changing of beam depth, span length, and beam flange width; especially in high-rise steel moment resistant frames that numbers of these connections are enormous and detailing of all of them is complicated and time consuming work. Besides proposed RBS connection detailing, decrease the stress concentration effects in the plastic hinge region of beam.

4. All of the analytical results of new RBS connection that were compared with ordinary RBS connection results show that the corrugated webs will improve the plastic stability and provide capability of large plastic rotation at the plastic hinge location without any appreciable buckling and brittle fractures in this region.

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