STEEL SEMIRIGID STRUCTURES ENERGY STATE UNDER SEISMIC ACTIONS

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ABSTRACT

Intended contribution proposes an energy-based approach to the assessment of capability of semirigid multi-storey steel structures to dissipate seismically induced energy via semirigidly connecting zones of the structure. The energy state of multi-storey structure is defined in terms of the energy balance equation. Total amount of seismically induced energy is divided into its classic components: kinetic energy, strain energy and dissipated energy. Dissipated energy is - in its turn - split into the amount dissipated by the structure itself (E_{ds}) and the amount dissipated by the semirigidly connected zones (E_{dc}). The last is computed as the equivalent of work performed by the bending moments associated to the semirigid connections through the relative rotations of the connections. Proposed procedure is further illustrated by several dynamic / seismical analyses of one multi-storey steel structure subjected to two reference earthquakes. Beam to column semirigid connections is of top - and seat - angle with double web-angles (TSDW) make up in several degrees of initial stiffness. The bending moment - relative rotation of semirigid connections are governed by Kishi - Chen relation. Obtained numerical results are presented into a comparative graphical manner. Short comments and conclusions end the contribution.

Keywords: Semirigidity, Energy State, Seismic Dissipated Energy

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1. INTRODUCTION

Since the semirigidity of skeleton structures has been formally accepted as a new beam-to-column connecting state European Committee For Standardization CEN. (1992), American Institute of Steel Construction, Inc. (1989). their response to seismic action focused on traditional components as storey lateral displacements, their static state - mainly expressed by the bending moment diagrams and the real behaviour of their semirigid connections – expressed via the $M - \theta_r$ relation Frye and Morris (1975), Kishi and Chen (1990), Chen and Lui (1991). Little has been done in regarding the semirigid connections not just in terms of their semirigid behaviour but, as structural zones where induced seismic energy could be dissipated. Traditional seismic analysis of structures still focuses on their mechanical state viewed as made up of the static-equilibrium state and kinematic compatibility state. Recently classical mechanical state has been enlarged by including energy state as a new component. While the mechanical parameters belonging to static and kinematic states (forces, displacements, strains, stresses) are vectorial entities, the parameters defining energy states are scalar entities which express synthetically the structural behaviour under seismic loads. It has to be emphasized that important mechanical features of a Civil Engineering type structure can only be involved in seismic analysis via energy. Such is the damping phenomenon that cannot be separated by its dual partner – the vibratory motion seismically induced.

The energy includes all structural aspects (seismic action, elastic state, inertia state, damping state) and associates them via mathematical relations that allow to track in time and space the development and evolution of the mechanical state of the structure. By the virtue of its scalar nature, the energy (either through its induced energy component E_i or through its dissipated energy component E_d) is a cumulative parameter capable to express not just the present (that can, also, be expressed by the traditional mechanical state) but, also, the past of the mechanical state. The energy state of a structure acted upon by an earthquake is not necessarily a totally new concept. The concept of energy state as a component of (classical) mechanical state has been - in the last decades - associated to the seismic action and response Akbas et al. (2001), Ordaz et al. (2003). Inclusion in the structural analyses - allowed for by energy formulation - of masses set in motion by the dynamic action of earthquake, of their induced velocities and accelerations, widens beneficially the frame of structural analysis and, in the same time, allows for a direct assessment of dynamic response un-affected by substitutive / corrective coefficients.

The intended contribution focuses on energy state of semirigid multi-storey steel structures acted upon by earthquakes. Energy state is defined by its components: seismically induced energy E_i, kinetic energy E_k, strain energy E_s and damping energy E_d. Similarly, to equilibrium equations associated to static state, to compatibility equations associated to kinematic state, energy state is governed by the energy balance equation:

$$E_i = E_k + E_s + E_d \tag{1}$$

The proposed contribution focuses on the contribution to dissipated energy componentE_d of semirigid connections of the structures in several cases of connecting solutions.

2. METHOD

The computation of energy components of MDOF dynamic systems Figure 1 requires the introduction of well-known vectors and matrices of traditional structural analysis:

Figure 1

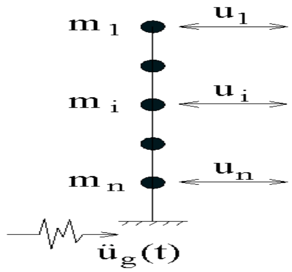

Figure 1 MDOF Dynamic System

u(nx1) - vector of DOF's (lateral storey displacements)

u˙(nx1) - vector of velocities of masses

u¨(nx1) - vector of accelerations

M(nxn) - inertial matrix

C(nxn) - damping matrix

R(nxn) - stiffness matrix

u¨_g - ground acceleration

Computation of energy components follows the literature dealing with energy of seismically acted upon structures Uang and Bertero (1990), Uang and Bertero (1988), Manfredi (2001). Therefore, the relations stated below govern the computation of energy components and are assessed by numerical integration.

The relative seismic input energy:

- $E_{i/r} = -\int_0^t \dot{u}(t)^T M \; \ddot{u}_g(t)\, dt$ (2)

The relative kinetic energy:

- $E_{k/r} = \frac{1}{2}\, \dot{u}(t)^T M\, \dot{u}(t)$ (3)

The dissipated (via damping) energy:

- $E_d = \int_0^t \dot{u}(t)^T C\, \dot{u}(t)\, dt$ (4)

The strain energy:

- $E_s = \int_0^t u(t)^T K\, \dot{u}(t)\, dt$ (5)

The specificity of semirigid structures is emphasized in the way the dissipated energy is generated. While in the case of rigidly connected structures, E_d component is associated to the inherent damping properties of the structure itself, in the case of semirigidly connected structures the induce seismic energy is dissipated by both the structure and the semirigid connections. The contribution of semirigid connections to the dissipated energy component is – in fact – the main objective of the contribution. Therefore, E_d component is splitted into E_{ds} – associated to the structure – and E_{dc} – associated exclusively to the semirgid connections.

$$E_d = E_{ds} + E_{dc} \quad (6)$$

Regarding E_{dc} component, it is generated during relative rotation component θ_r and its computation is based on the equivalence of elementary work dL_j performed by bending moment M_j of each j connection through elementary relative rotation $d\theta_{r,j}$:

$$dL_j = M_j \, d\theta_{r,j} \quad (7)$$

Where

$$d\theta_{r,j} = \dot{\theta}_{r,j} \, dt \quad (8)$$

It leads to a total amount of dissipated energy via semirigid connections:

$$E_{dc} = \sum_{j=1}^{m} \left(\int_0^{tc} M_{\mathbf{j}} \, \dot{\theta}_{\mathbf{r,j}} \, dt \right) \quad (9)$$

Following a structural analysis program devoted to semirigid multi-storey steel structures, Seismostruct Seismosoft. (2022). M_j and $\theta_{r,j}$ are computed as functions of time. Integrating process (9) is computed by summing up the elementary quantities associated to an elementary time step

dt = 0.02 sec.

3. STRUCTURES, SEMIRIGID CONNECTIONS, SEISMIC ACTIONS

In what follows, computation of dissipated energy E_d – and implicitly of its E_{ds} and E_{dc} components – is associated to a 4 storey 3 span semirigid steel (of S355 class) structure Figure 2.

Figure 2

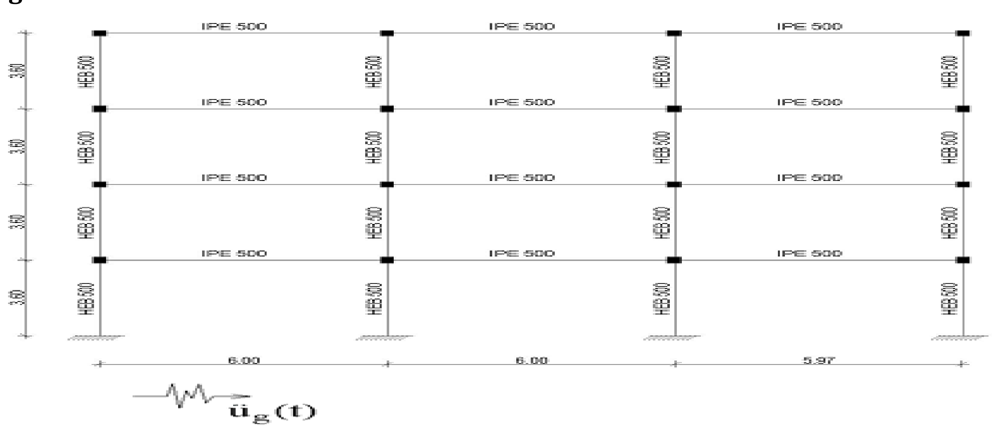

Figure 2 Four Storey Frame

The semirigid connections are of top – and seat- angle with double web-angles (abbreviated as TSDW, from here on) type Figure 3.

Figure 3

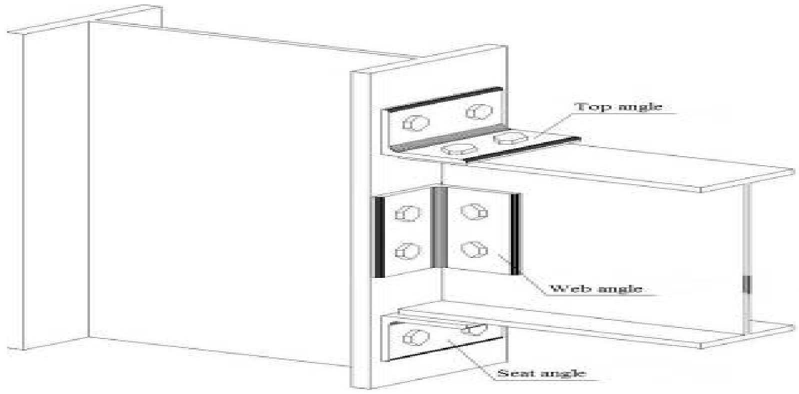

Figure 3 TSDW Semirigid Connection

The Kishi-Chen (three parameter) power model Kishi and Chen (1990). of the M-θ_r curve is adopted for the practical modelling of the connections, as described in Chen and Kim (1997).

The mechanical and geometrical features of semirigid connections are presented in Table 1 and Table 2, respectively.

Table 1

Table 1 Mechanical Characteristics of the TSDW Semirigid Connections

Connection	Node TSDW1	Node TSDW2	Node TSDW3
R_i (kNm/rad)	102200	205500	302200
M_u (kNm)	331.615	433.902	461.318
n (-)	1.151	0.891	0.827

R_i - initial connection stiffness

M_u - ultimate connection moment capacity

n – shape parameter

Table 2

Table 2 Geometrical Characteristics of the TSDW Semirigid Connections

Connection	Node TSDW1	Node TSDW2	Node TSDW3
t_{sup};t_{inf} (mm)	14	16	16
t_{in} (mm)	9	10	10
l_{sup};l_{inf} (mm)	200	200	200
l_{in} (mm)	400	400	400
Bolt size	M20	M20	M24
g_{sup} (mm)	68	65	63

g_{in} (mm)	60	54	52

t_{sup}, l_{sup} - thickness and length of top angle wing

t_{inf}, l_{inf} - thickness and length of seat angle wing

t_{in}, l_{in} - thickness and length of web angle wing

g_{sup} - distance between the center of the bolt hole and the top angle's heel in the wing adjacent to the column face

g_{in} - distance between the center of the bolt hole and the web angle's heel

Seismic actions are introduced via recorded ground accelerations of El Centro 1940 NS Figure 4 and Vrancea 1977 NS Figure 5 earthquakes, scaled down to peak values of 0.20g and 0.25g, respectively.

Figure 4

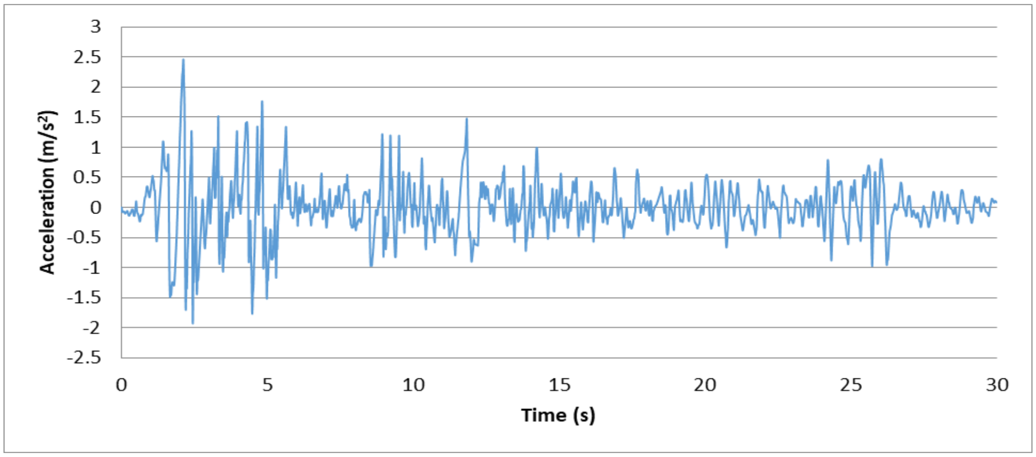

Figure 4 El Centro 1940 NS – Ground Acceleration

Figure 5

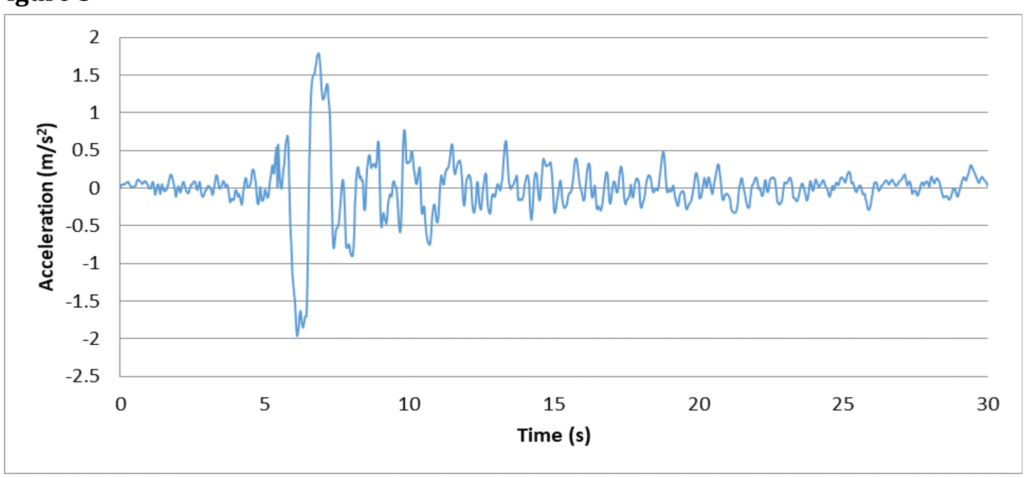

Figure 5 Vrancea 1977 NS – Ground Acceleration

4. RESULTS AND DISCUSSION

Computed results include seismically induced energy E_i, dissipated energy by the structure itself E_{ds}, dissipated energy by the semirigid connections E_{dc} and the total dissipated energy E_d. The results are presented graphically in a comparative manner Figure 6, Figure 7, Figure 8, Figure 9,Figure 10,Figure 11,Figure 12,Figure 13,Figure 14,Figure 15, Figure 16,Figure 17,Figure 18,Figure 19,Figure 20. The fraction of critical damping is considered ζ= 5%. The presented results are excerpts from a larger study regarding the capability of semirigid steel structures to dissipate seismically induced energy.

Figure 6

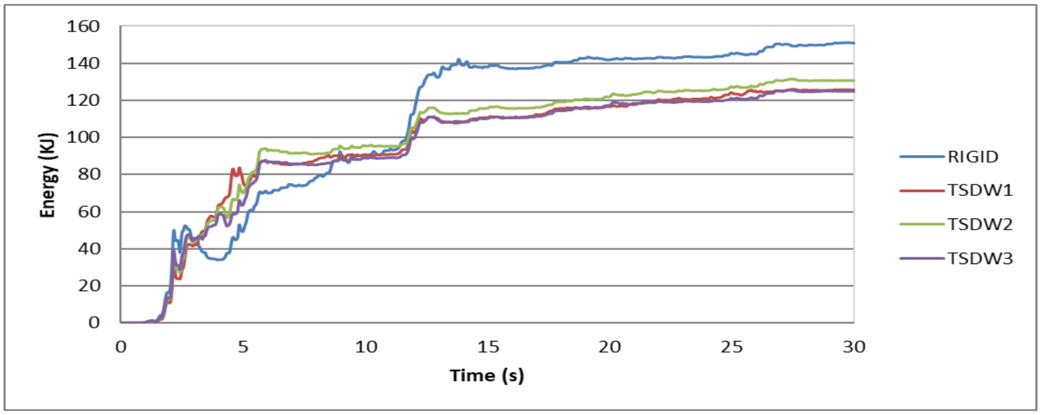

Figure 6 Input Energy $\mathbf{E_i}$– El Centro 1940 NS

Figure 7

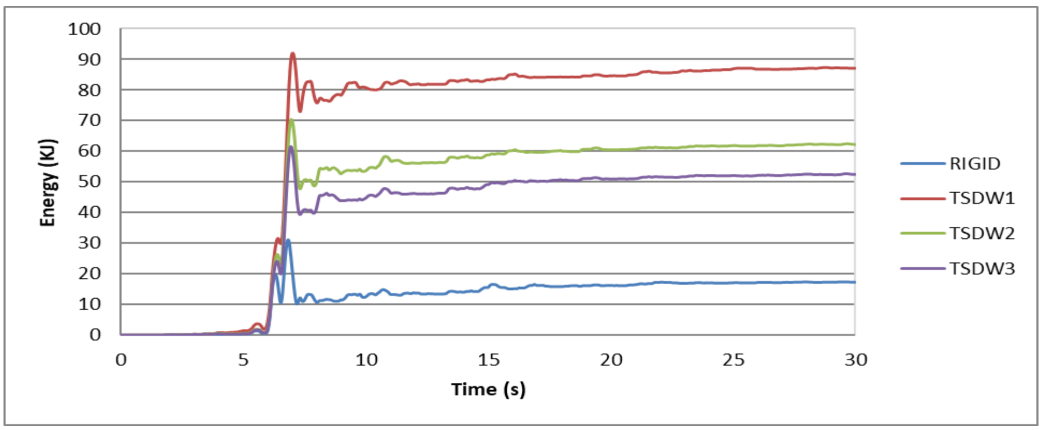

Figure 7 Input Energy $\mathbf{E_i}$– Vrancea 1977 NS

Figure 8

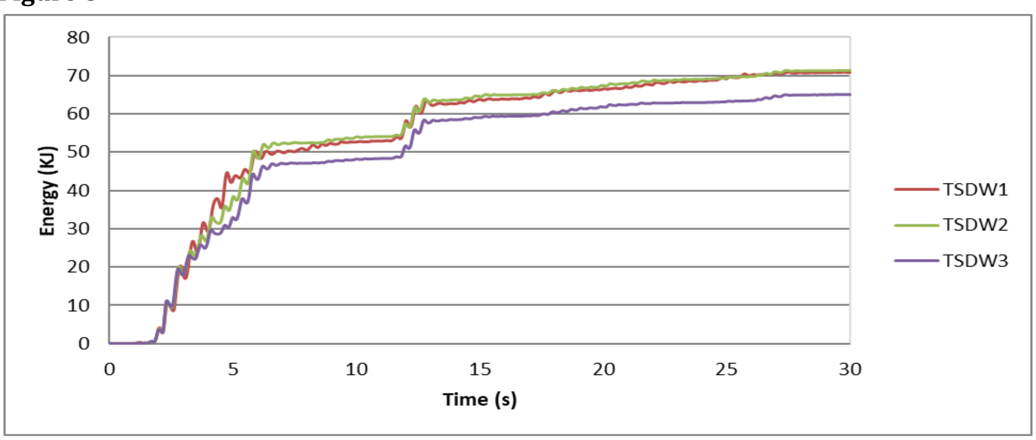

Figure 8 Dissipated energy $\mathbf{E_{dc}}$ – El Centro 40 NS

Figure 9

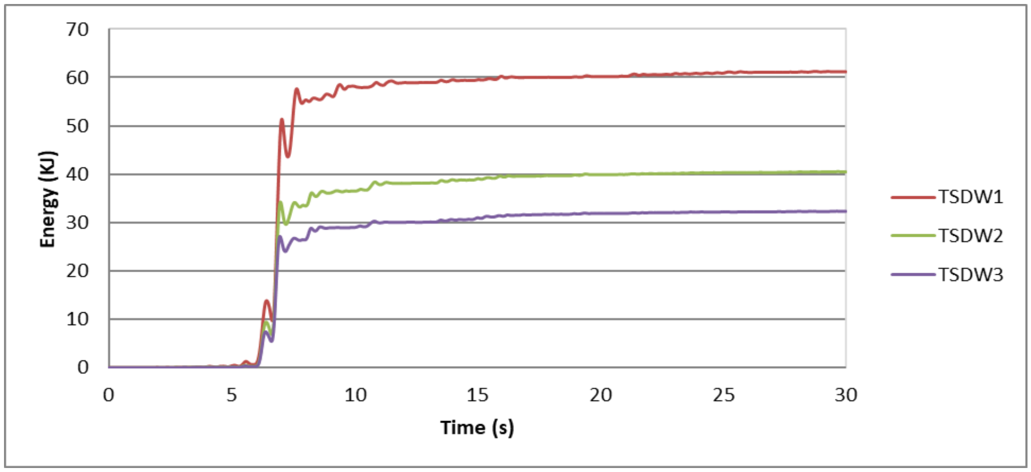

Figure 9 Dissipated Energy$\mathbf{E_{dc}}$ – Vrancea 1977 NS

Figure 10

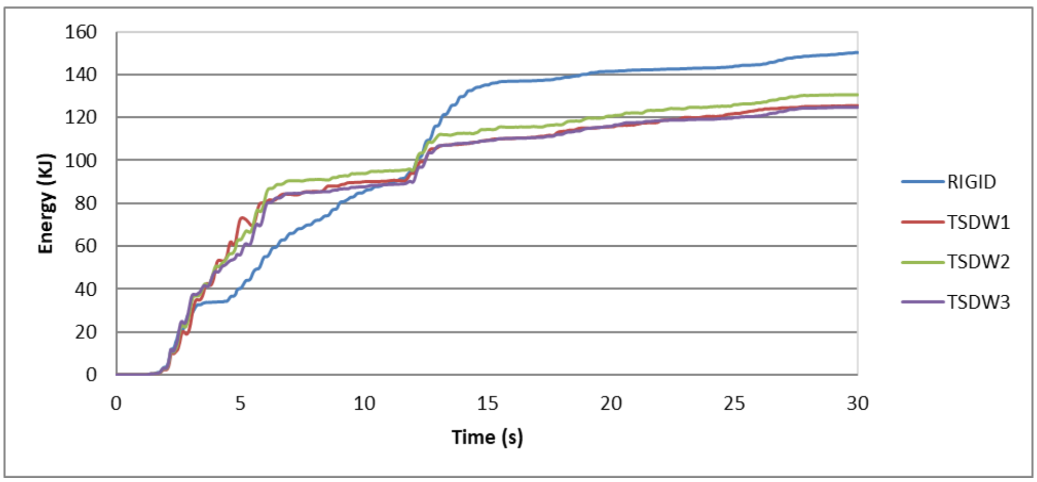

Figure 10 Total Dissipated Energy $\mathbf{E_d}$ – El Centro 40 NS

Figure 11

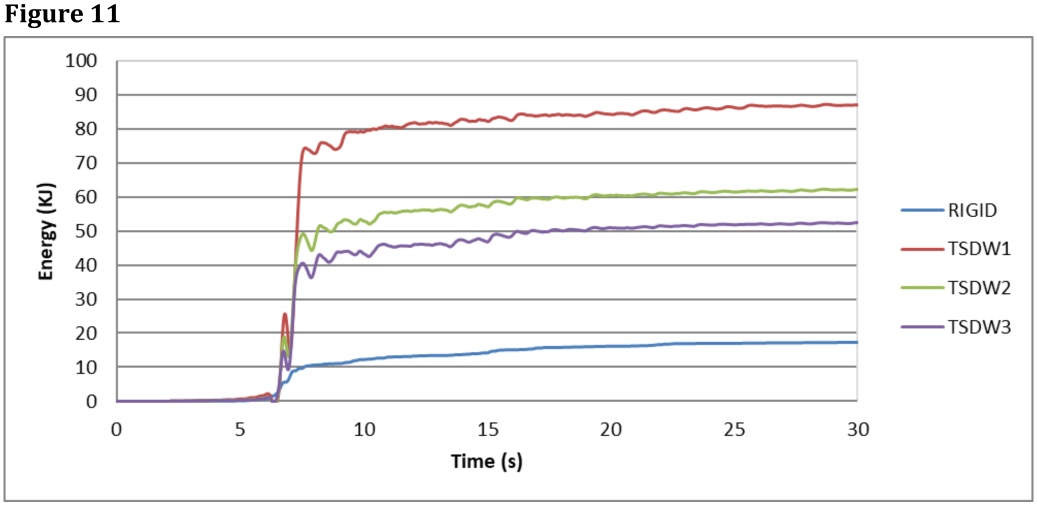

Figure 11 Total Dissipated Energy $\mathbf{E_d}$ – Vrancea 1977 NS

Figure 12

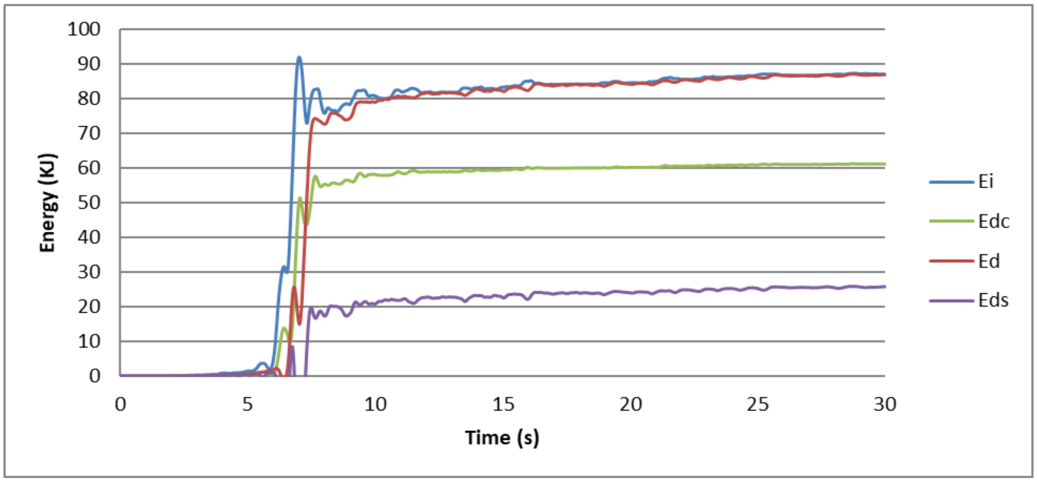

Figure 12 Energy Components – Vrancea 1977 NS – TSDW1

Figure 13

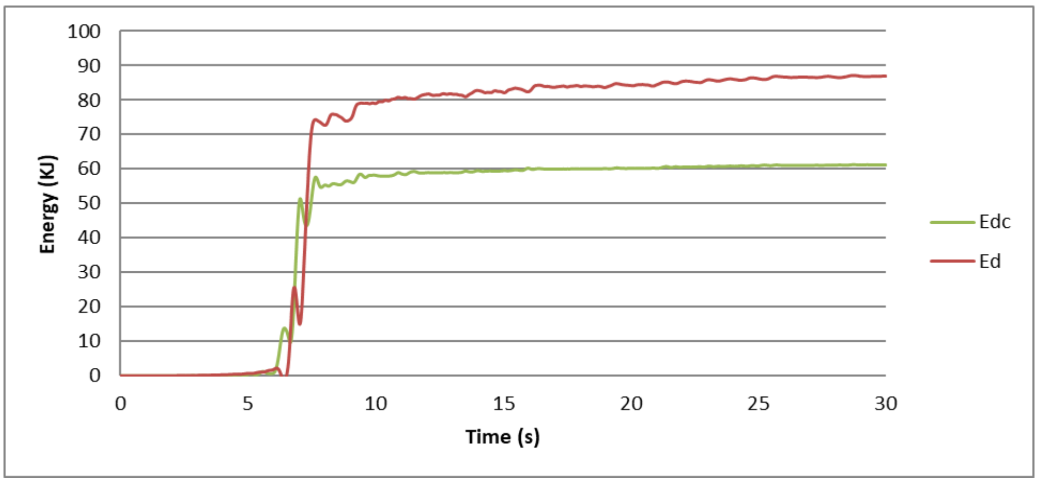

Figure 13 Energy Components $\mathbf{E_{dc}}$ And $\mathbf{E_d}$ – Vrancea 1977 NS – TSDW1

Figure 14

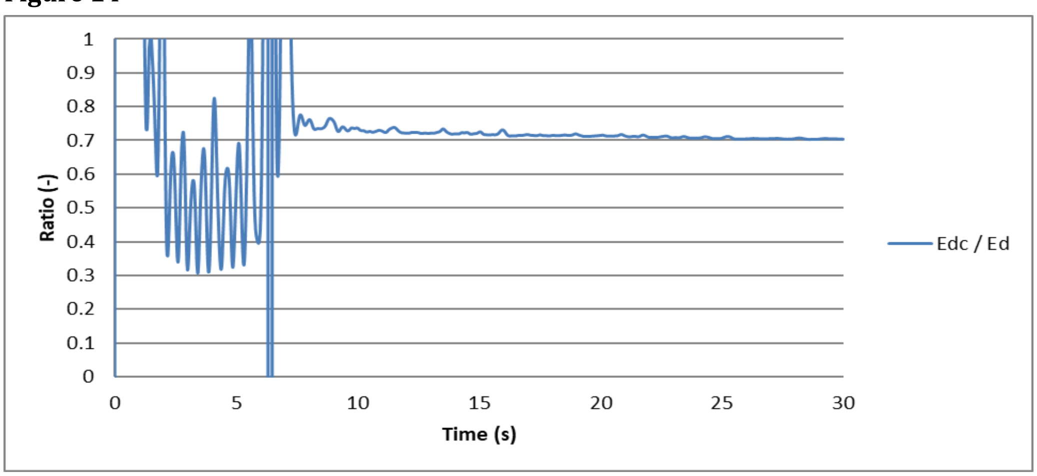

Figure 14 Contribution of $\mathbf{E_{dc}}$ To $\mathbf{E_d}$– Vrancea 1977 NS – TSDW1

Figure 15

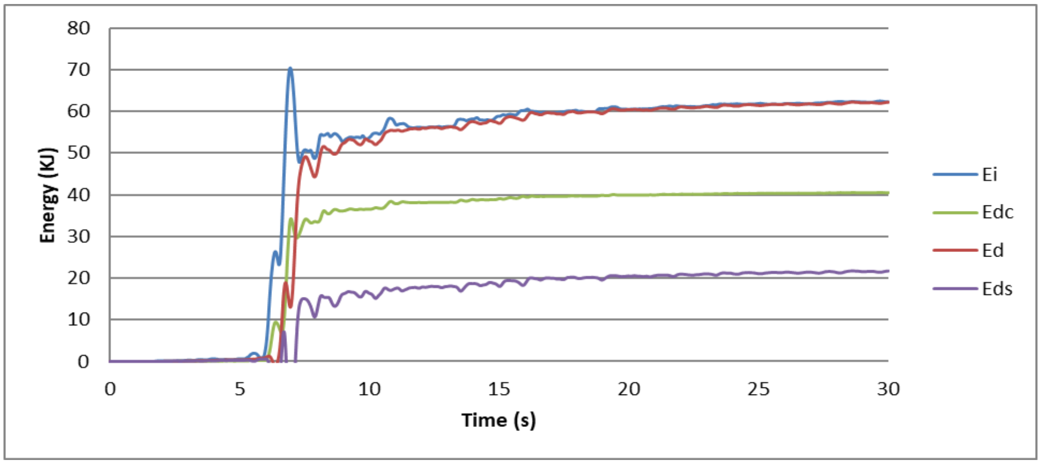

Figure 15 Energy Components – Vrancea 1977 NS – TSDW2

Figure 16

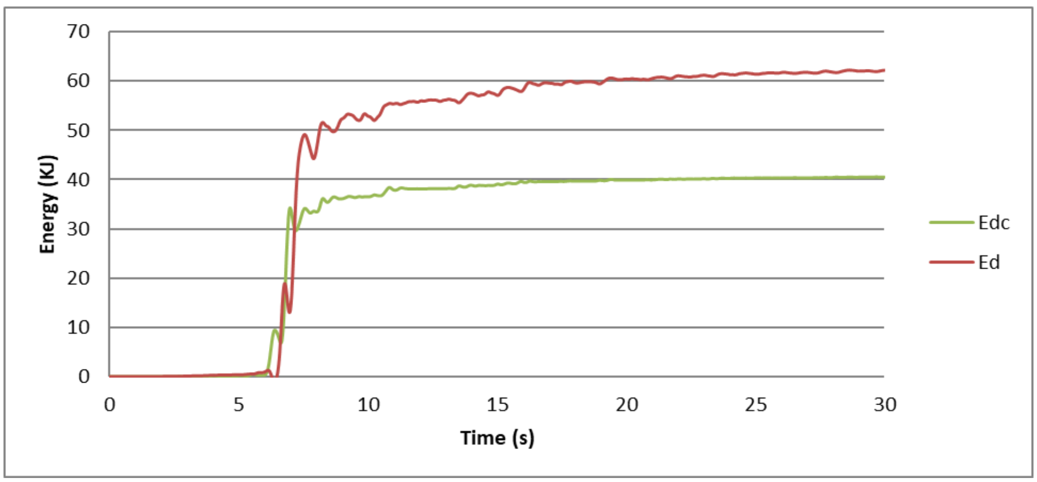

Figure 16 Energy Components $\mathbf{E_{dc}}$ And $\mathbf{E_d}$ – Vrancea 1977 NS – TSDW2

Figure 17

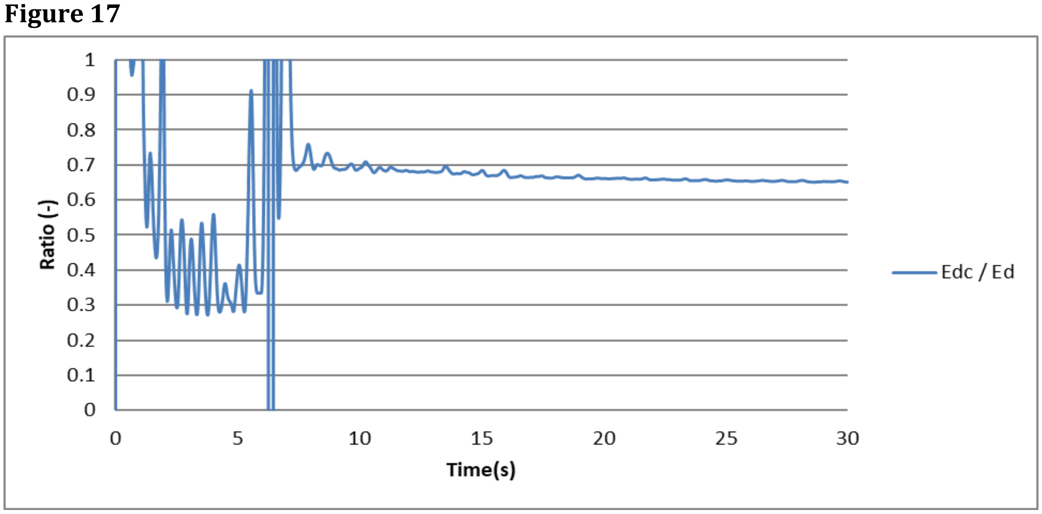

Figure 17 Contribution of $\mathbf{E_{dc}}$ To $\mathbf{E_d}$ – Vrancea 1977 NS – TSDW2

Figure 18

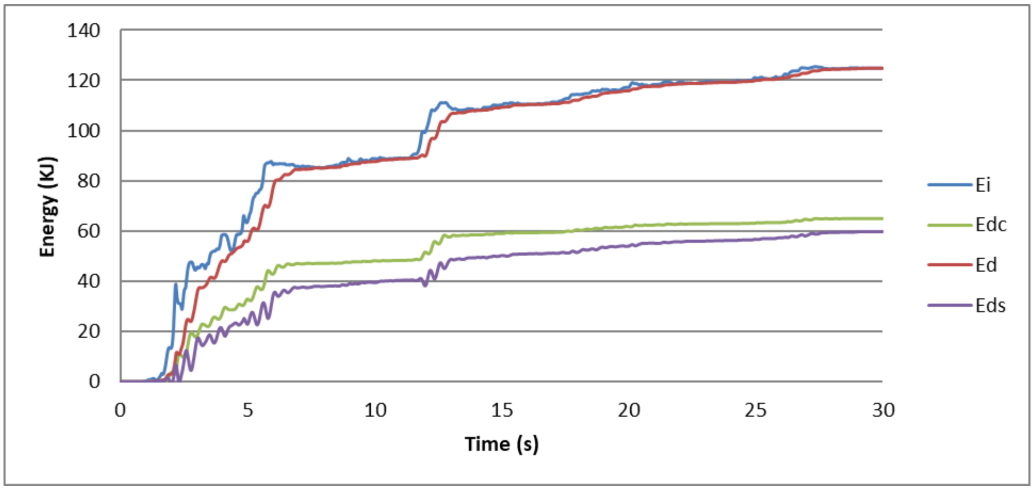

Figure 18 Energy Components – El Centro 40 NS – TSDW3

Figure 19

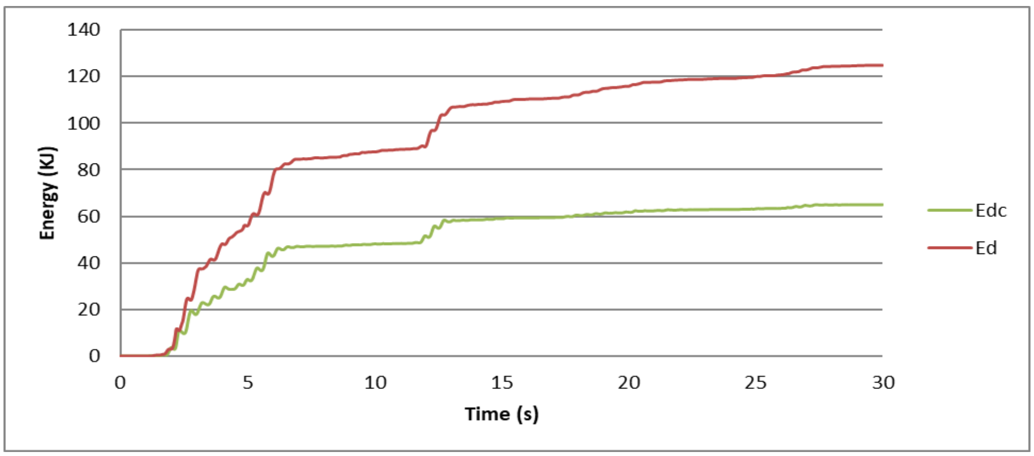

Figure 19 Energy Components$\mathbf{E_{dc}}$ And $\mathbf{E_d}$ – El Centro 40 NS – TSDW3

Figure 20

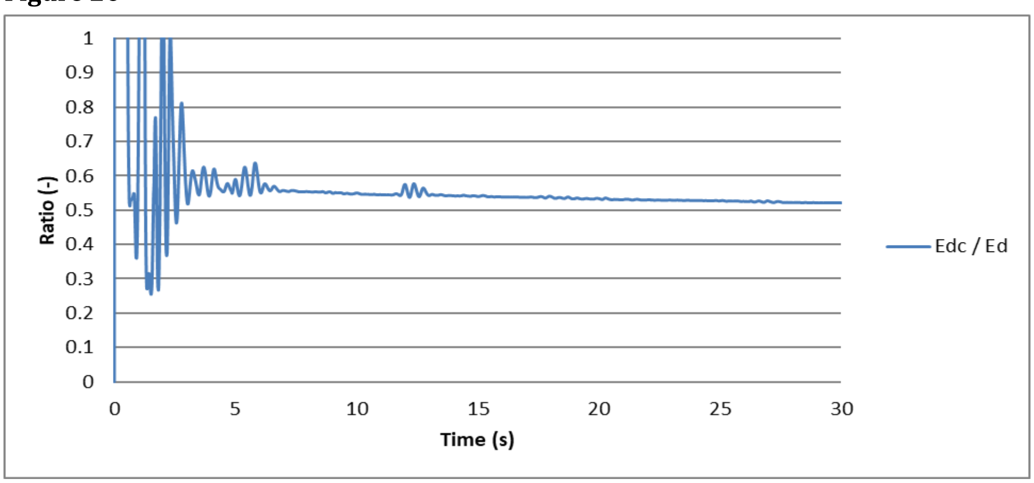

Figure 20 Contribution of $\mathbf{E_{dc}}$To $\mathbf{E_d}$ – El Centro 40 NS – TSDW3

The two components of the dissipated energy are separately emphasized for each case of mechanical make-up semirigid beam-to-column connections. Clear remarks regarding the amount of dissipated energy by the structure itself and by the semirigid connections are possible from the comparative graphical manner the results are presented.

As it can be seen from the results, the dissipated energy via the semirigid connections E_dc accounts for an important percent (50-70%) of the total dissipated energy E_d.

5. CONCLUSIONS

The proposed objective has been accomplished by computed energy parameters associated to dissipation capability of semirigid connections. The first conclusion to presented results is that semirigidity of beam-to-column connections is capable of dissipating seismically induced energy.

A second conclusion can be drawn referring to the amount of dissipated energy by semirigid connections E_{dc} as part of the total dissipated energy E_d. It may be concluded that this part depends to a large extent on both seismic action and rigidity of the connection. Therefore, in the design activity of semirigid multi-storey steel structures, the specificity of semirigid connections should be closely associated to the specificity of seismic actions.

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

None.

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