BEHAVIOR FACTOR EVALUATION BASED ON SDOF SYSTEM PRESENTATION AND ENERGY APPROACH

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1 INTRODUCTION

The modern seismic resistant design concepts are theoretically based on the assumption that wide class of structures are capable of dissipating energy through inelastic deformations. It is recommended to use ductile structures unless the ductility limits remain within the prescribed limits. The seismic loads can significantly be reduced if the structure is designed to be dissipative. The numerical verification of the behavior factor (q-factor) becomes a subject of intensive research work during the past decade, see [3],[6] and [8]. This is a good chance to check the validity of design theory assumptions and to make structural performance more predictable from engineering point of view. Significant progress is made towards advanced modeling of structures in order to determine dissipated energy more precisely. Most of the existing methods for the q-fact evaluation are discussed in [6].

Following some authors [3],[4] and [6] the proper definition of the q-factor should be done using equivalent single degree of freedom (SDOF) system, obtained similarly to modal transformation. This step requires the horizontal displacements shape function to be previously known. This approach is obviously approximate since the displacement distribution in elevation does not remain constant during the time. In [3] the q-factor is defined as ratio between the elastic peak response and the maximum shear that can withstand the equivalent SDOF system assuming elastic-perfectly plastic material law. Kato [4] gives a measure for the force reduction factor using energy balance equation assuming that the ultimate limit state is reached and displacement shape function can be simplified as a result of that. Finally the Kato's method requires the dissipated energy for the entire structure to be determined. The energy concept for the q-factor determination is successively developed for practical use by Akiyama [1] where the dissipated energy for each story is needed for calculations. However the ultimate state criterion is still open to debate. The basic problem that arise is how the ultimate limit state, in particular, for steel structures, should be defined. Criteria that are based on local or global ductility can be employed [2] and [6] but all of them are dependent on the type of structure and their connections. There is not an established common criterion to indicate properly whether the ultimate state of a structure is reached or not.

In this paper the expression for the q-factor is derived basing on the energy balance equation, applied to ultimate state. Near this state the response of a structure can be represented considering the equivalent SDOF system, whose parameters are properly defined. In contrast with [3] the displacement shape functions are selected among a set of functions, typical for different types of collapse mechanisms. It is expected this procedure to improve the accuracy of the q-factor evaluation. The application of the results derived herein is illustrated considering four story-two bays steel frame. The numerical results for the q-factor are further discussed.

2 SHORT DESCRIPTION OF THE ALGORITHM

The following assumptions are suggested in the paper:

1) The only horizontal displacements of the floor levels will be considered in analysis;

2) The plastic work capacity, W_p , is calculated when interstory drift reaches 3% average value on the record duration ;
3) The distribution of story displacements in elevation depends only on a single parameter. For convenience the top displacement is chosen to be such parameter.
Following the energy approach, the limit state of a structure is is observed if the energy dissipation demand, denoted by E_p, exceeds the plastic work capacity [4]. Thus, the structure will be prevented from collapse if

$$E_p \le W_p \tag{1}$$

The deformed shape is represented by the vector of horizontal floor displacements, $\{v\}$. Mathematically the vector $\{\Phi\}$ represents the shape function. Its components are normalized with respect to the top displacement. The shape vector should be known in advance to perform further steps. It is proposed herein this vector to be identified among the vectors, corresponding to feasible collapse mechanisms, see Figure 1. For a typical moment resisting steel frame, shown in Figure 1 collapse mechanisms and vectors may be suggested as shown. Identification is made basing on the generalized displacement v^* introduced according to equation:

$$v^* = \frac{\{\Phi\}^T[m]\{v\}}{\{\Phi\}^T[m]\{\Phi\}} \tag{2}$$

for each collapse mode. According to assumption 3) it follows that

$$\{v\} = \{\Phi\}v_T \tag{3}$$

where v_T denotes the top displacement. Equation (1) is applied to each of expected collapse mechanisms. Note that identical values for v^* and v_T. can be expected if the condition (3) is satisfied. Thus the difference between both displacements indicates whether the studied mechanism is close to the real one or not. After doing that the $\{\Phi\}$-vector is already known.
The next step is to transform the governing system of equations

$$[m]\{\ddot{v}\} + \{f\} = -[m]\{1\}\ddot{v}_g \tag{4}$$

into equivalent single equation of motion, corresponding to a SDOF system.
In equations (2) and (4) $[m]$ is the floor mass matrix, $\{f\}$ is the vector of internal forces at the floor levels, $\{1\}$ is the unity vector and $\ddot{v}_g$ denotes the horizontal ground acceleration. Details on the SDOF equation modification are given by Fajfar [3]. The basic notations in this transform are listed bellow

$$m^* = \{\Phi\}^T[m]\{1\}; \quad \ddot{v}_T^* = \psi\ddot{v}_T \quad , \quad \dot{v}_T^* = \psi\dot{v}_T \quad , \quad v_T^* = \psi v_T \tag{5}$$

where

$$\psi = \frac{\{\Phi\}^T[m]\{\Phi\}}{m^*}$$

The following quantities are also introduced in the calculations:

$$k^* = \{\Phi\}^T [k] \{\Phi\} \quad , \quad \omega^{*2} = k^* / m^* \tag{6}$$

where k^* and ω^* are the stiffness and circular frequency, respectively, both associated with the equivalent SDOF system. The transformed equation of motion for this system is

$$m^* \ddot{v}_T^* + F^* = -m^* \ddot{v}_g \tag{7}$$

The internal restoring force, associated with the equivalent SDOF system is denoted by F^*. This force is found to be $F^* = \{\Phi\}^T \{f\}$.
The energy balance equation for the structure at ultimate state is

$$E_{inp} = E_k + E_p \tag{8}$$

The strain energy in the above equation is neglected. The corresponding counterparts of this equation are described and evaluated bellow.
The left-hand term represents the input energy, including the effect of damping, that is

$$E_{inp} = \frac{1}{2} \left(\frac{T^* g}{2\pi} \right)^2 m^* R_e^2 \tag{9}$$

where R_e is the elastic response spectrum, normalized to unit peak ground acceleration and g is gravity acceleration. The kinetic energy, used in the right-hand side of equation (8) is then evaluated by the expression

$$E_k = \frac{1}{2} \left(\frac{T^* g}{2\pi} \right)^2 m^* \frac{R_e^2}{q^2} \tag{10}$$

where q is the behavior factor and T^* is the period of vibration of the equivalent SDOF system.
The final result for the dissipated energy is obtained assuming that ultimate state is reached and equality in equation (1) takes place, thus

$$E_p = W_p = \frac{(R_e g)^2}{\psi k^*} (m^*)^2 \frac{1}{q^2} \eta^* \tag{11}$$

The parameter η^* involved in above equation is the accumulated ductility . Using equation (11) and assuming that the equivalent SDOF system has elastic-perfectly plastic force-displacement relationship, one may write

$$\eta^* = \frac{E_p k^*}{(F_y^*)^2} \psi \tag{12}$$

where F_y^* is the yield strength of the equivalent SDOF system.

The behavior factor is then evaluated substituting equations (9), (10) and (11) into (8):

$$q = \sqrt{1 + \frac{2\eta^*}{\psi}} \tag{13}$$

3 NUMERICAL RESULTS AND CONCLUSIONS

Four story two bay plane steel frame, taken from reference [5], is used to illustrate the q-factor evaluation basing on the above formulae. The story height is 3.0 m, beam span is 6.0 m. All masses are lumped at the beam-to-column joints and are identical. Two strong motion acceleration records are used: El-Centro, 18 May, 1940 and Vrancea, 4 March, 1977. Both records are represented by its N-S component. The feasible collapse mechanisms for this frame are given in Figure 1. The fundamental period of the frame is 1.27 sec. It is seen from the Figure 2 that second mechanism provides the closest generalized displacement to the top displacement. It means that the second mode of the shape function will be prevailing. It is found that for this mode, using Equation 5, $\Psi=0.852$. Acceleration multipliers are taken 3.75 for El-Centro acceleration record and 1.16 for Vrancea acceleration record. The values of the q-factor that are calculated using equation (13) are as follows: q=7.511 for El-Centro and q=4.582 for Vrancea. It is found that the results obtained by this method are rather conservative than the results, obtained by other methods. It is obvious that the frame dissipate more energy in using El-Centro record. The possible reason for that is found to be in the rate of energy dissipation, which is greater in Vrancea case. The frame, subjected to Vrancea record yields very fast and very soon it is incapable to dissipate more energy.

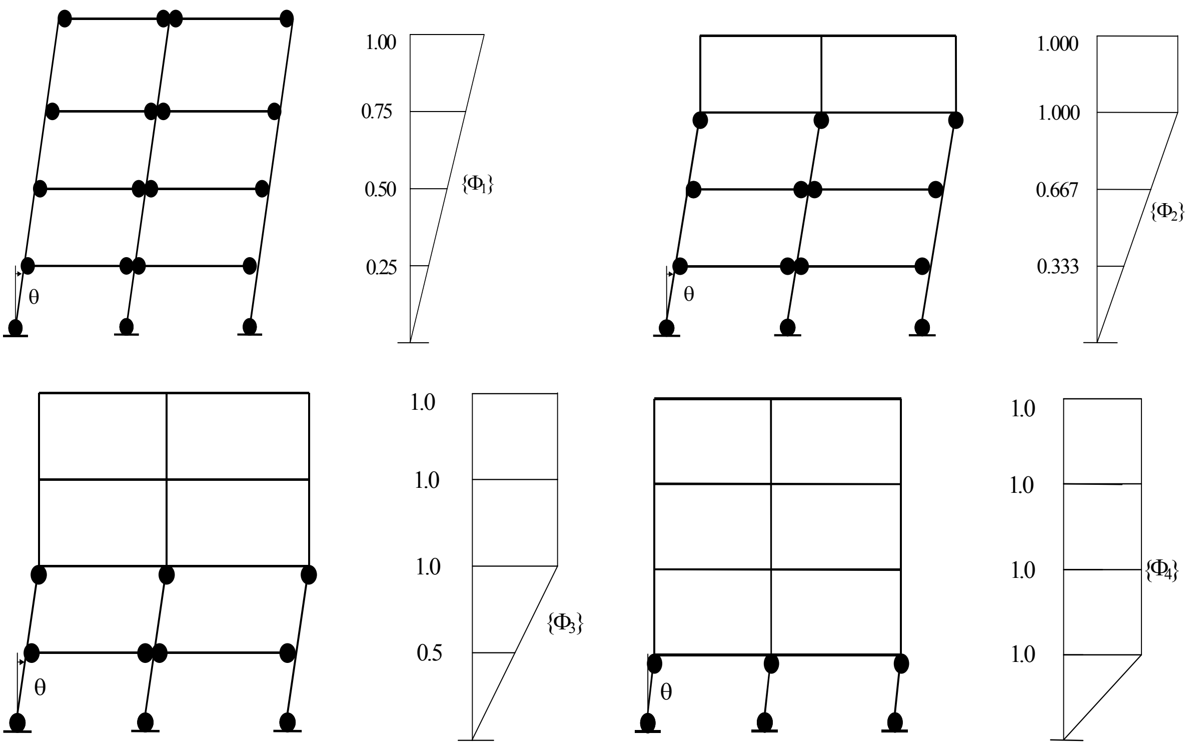

Figure 1. Feasible collapse mechanisms for the studied frame.

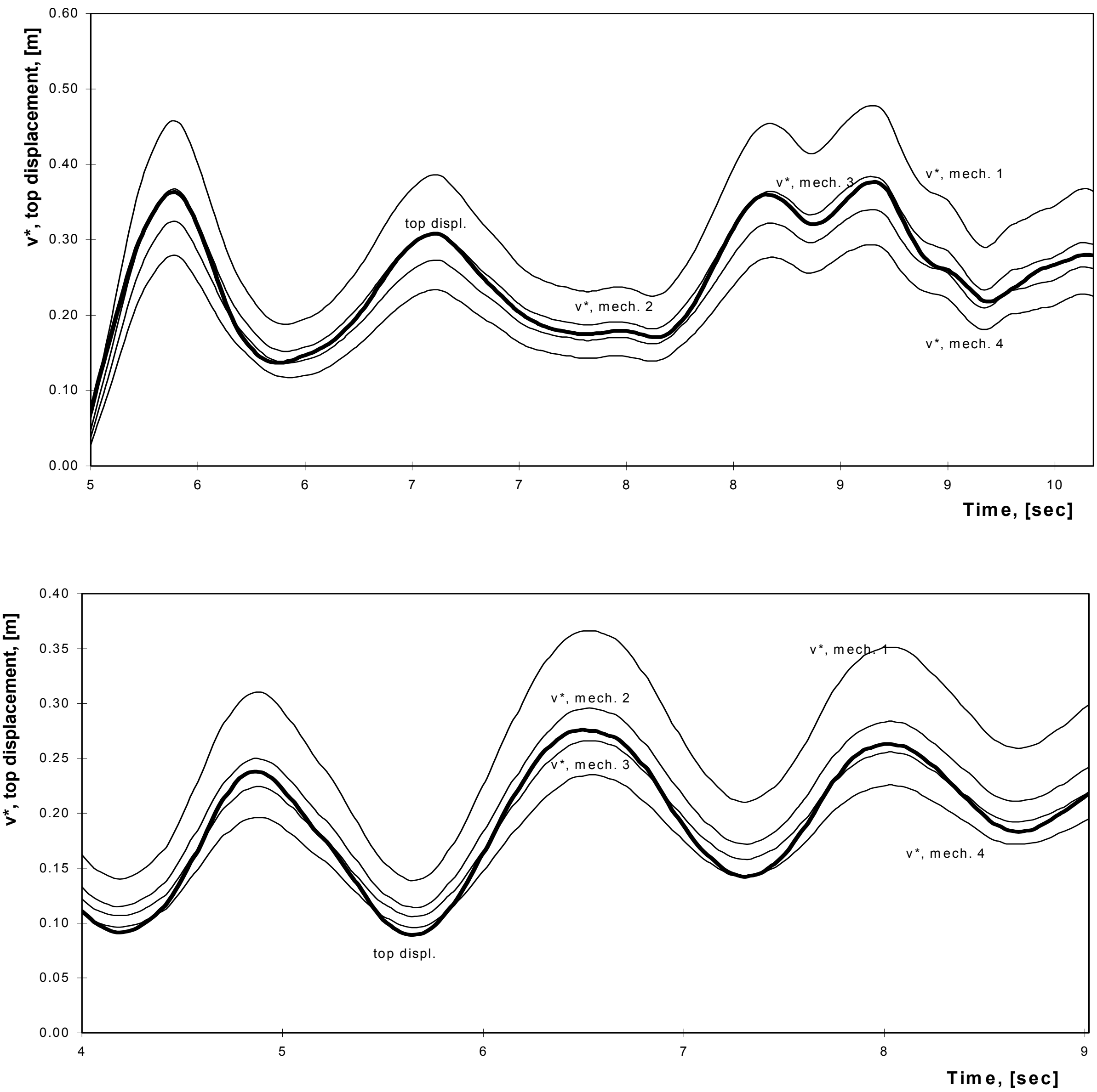

Figure 2: Collapse mechanism identification using El-Centro and Vrancea records.

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