DESIGN PROCEDURE FOR BUCKLING RESTRAINED BRACES TO RETROFIT EXISTING R.C. FRAMES

T. Albanesi[1], A. V. Bergami[2] and C. Nuti[3]

[1] *Assistant Professor, Department of Structures, Dis, University of Roma Tre, Rome, Italy*
[2] *Fellow Researcher, Department of Structures, Dis, University of Roma Tre, Rome, Italy*
[3] *Full Professor, Department of Structures, Dis, University of Roma Tre, Rome, Italy*
Email: t.albanesi@uniroma3.it, abergami@uniroma3.it, c.nuti@uniroma3.it

ABSTRACT :

Existing reinforced concrete frame buildings with non-ductile detailing suffered severe damage and caused loss of life during earthquakes. Different rehabilitation systems have been developed to upgrade the seismic performance of this kind of structures before being subjected to an earthquake: in particular, buckling restrained steel braces (BRB) offer many advantages.
BRB differs from a conventional brace in that it is capable of yielding both in tension and compression instead of buckling thus exhibiting very favorable energy-dissipating characteristics.
The present paper deals with the seismic protection of reinforced concrete frames. In particular a displacement-based procedure to design dissipative BRB for the seismic protection of masonry-infilled frames is proposed. A two-fold performance objective is considered to protect the structure against the collapse (ULS) and the non-structural damage (DLS) by limiting global displacements and interstorey drifts so that structural and infill integrity is granted under a given seismic event. Positioning these devices in a structure to maximize their effectiveness at minimum cost is a very important issue which is considered too.
As an example, an infilled-frame building, designed according to the non-seismic Italian Code and thus only for vertical loads, is analyzed. A numerical study to investigate its seismic behavior with and without BRB is carried out. Non linear static and dynamic time-history analyses to assess the effectiveness of the proposed rehabilitation design procedure are performed.

KEYWORDS: structural response, infilled r.c. frame, seismic protection.

1. INTRODUCTION

Buildings not designed according to seismic codes present structural deficiencies and might suffer damage and collapse when subjected to seismic action; in this case rehabilitation aims to guarantee life safety of people. Buildings designed according to modern seismic concepts can usually resist even to strong seismic action thus preventing collapse but, at the same time, accepting some damages in structural and non structural components. In this case it might be reasonable to reduce structural vulnerability. Common retrofitting aims to enhance structural strength (reducing ductility demand) or dissipation and ductility (reducing drift and allowing plastic deformations).
In the last decade a very diffuse retrofitting system uses buckling restrained dissipative steel braces (BRB) that offer some unquestionable advantages: openings adaptive, irrelevant weight increase, easy installation and minimum interference to buildings use, strength increase controlled, relevant dissipation increase.
The bracing member consists of a core steel plate, endowed with a special coating to reduce friction and encased in a concrete-filled steel tube preventing steel core buckling in compression. Then, axial forces are absorbed by the core only, that is free to lengthen and shorten, thus dissipating energy by yielding both in tension and compression.
As any metallic damper, BRB behavior depends on its geometry and mechanical characteristics. These devices provide a stable hysteretic energy dissipation with a cyclic response practically coincident with the steel constitutive law. The steel core can be realized in various ways according to the employment: steel plates are useful with thin walls and H-shape steel provides high stiffness and resistance. These devices can replace a whole brace element or, especially in case of particularly small displacements and high stiffness, they can assume the configuration of short elements connected in series to a traditional brace.
In this work, a design procedure to determine the characteristics of dissipative steel braces *B* to retrofit an existing building *S* is discussed and verified. The procedure is based on displacement response control and the use of well known non linear static analysis.

2. DESIGN METHOD

2.1. Relevant Parameters

In BRB design it is useful to be aware of dissipating braces effects on structural behavior:
1. initial stiffness increasing, 2. strength increasing, 3. modal shapes changing, 4. energy dissipation increasing. Effects 1, 2 and 3 influence the structural capacity curve while effect 4 influences the demand curve.
A reasonable force-displacement model to describe BRB behavior is the bilinear law that is defined by elastic axial stiffness K'_b, yielding force F'_{by} and hardening ratio β_b.
So the main variables in design procedure are the following:
1. the plano-altimetric position of BRB that influences device sizing because it modifies the braced frame deformed configuration;
2. the stiffness K'_b that directly affects the elastic stiffness of the braced structure;
3. the yielding force F'_{by} (or the yielding displacement D'_{by}) that determines the point over which the BRB can be effective thus influencing both the resistance of the braced structure and its energy dissipation capacity;
4. the hardening ratio β_b that affects both the resistance of the braced structure and its dissipative capacity.
Such characteristics depend on mechanical properties of materials (yielding strength f_{by}, elastic modulus E_b, hardening ratio β_b) and on BRB geometry (length l_b, inclination θ_b, cross section area A_b).
Generally, it is possible to recognize in BRB a portion of length l_{b1} and section A_{b1} in which yielding develops and a more resistant remaining portion of length l_{b2}=l_b-l_{b1} and section A_{b2} (错误！未找到引用源。(b)). Such elements are connected in series so that it follows:

$$K'_b = \frac{K'_{b1}K'_{b2}}{K'_{b1}+K'_{b2}} \tag{1}$$

$$F'_{by} = f_{by}A_{b1} \tag{2}$$

$$D'_{by} = \frac{F'_{by}}{K'_{b1}} = \frac{f_{by}}{E_b}l_{b1} \tag{3}$$

where K'_{b1}=E_bA_{b1}/l_{b1} is the elastic stiffness of the dissipative portion and K'_{b2}=E_bA_{b2}/l_{b2} is the brace stiffness (without damper).
In case of whole dissipative brace, l_b=l_{b1}, A_b=A_{b1} and K'_b=K'_{b1}.
The system B, connected to the structure S, is defined by the horizontal components:

$$K_b = K'_b \cos^2\theta_b \tag{4}$$

$$F_{by} = F'_{by}\cos\theta_b \tag{5}$$

$$D_{by} = D'_{by}/\cos\theta_b \tag{6}$$

In a design procedure it is reasonable to set the following elements:
1. material properties (f_{by}, E_b, β_b), that are limited to commercial products;
2. planar configuration of braces (l_b, θ_b) that is determined by architectural constraints;
3. yielding displacement D_{by} that depends on expected displacements of braced structure.
Finally BRB design, as discussed in this paper, reduces to determine the stiffness K_b.

2.2. BRB configuration

Placement in plant and elevation together with installation modality is a relevant matter in BRB design. Geometric restraints usually influences braces positioning, in particular this happens in presence of doors, windows, passages, infill and so on.

Braces can be inserted in the frame bays or placed in an external structure to be connected to the existing one. Then BRB placement should be analyzed case by case even if some general considerations can be drawn. Braces positioning influences both structural deformation, since it modifies modal shapes, and damping devices effectiveness.
The addition of braces should reduce or eliminate eventual translation-rotation coupling effects, induce constant or linearly increasing interstory drifts and maximize damping and minimize costs (Zhang and Soong, 1992).
Different criteria to optimize BRB stiffness distribution are proposed in scientific literature: constant at each story, proportional to story shear, proportional to interstory drifts. In this work the latter is assumed, then brace stiffness K_{bj} depends on interstory drift δ_j:

$$K_{bj} = K_b c_{bj} \tag{7}$$

where:

$$c_{bj} = \frac{\delta_j}{\max_j\{\delta_j\}} \tag{8}$$

This is a simple criteria aiming to make the deformation of the braced frame to be linear.

3. *Proposed Design Procedure*

The following proposed design procedure for buckling restrained dissipative braces (BRB) generalizes Kim and Choi's approach (2004). In the latter the required energy dissipation is provided by the hysteretic deformations of the BRB only while the structure is assumed to remain elastic. This assumption makes the method not always applicable.
Generally, in case of strong seismic events, the structure could undergo plastic deformations that should be take into account in BRB design procedure.
The procedure is iterative because the addition of BRB modifies the structural response and in particular the capacity curve that has to be updated as long as BRB characteristics are being defined.
The proposed design procedure is based on the well known Capacity Spectrum Method where the total effective damping of a braced structure $\nu_{eq,S+B}$ is expressed in terms of equivalent viscous damping as a linear combination of the equivalent damping of the structure only $\nu_{eq,S}$, the equivalent damping of BRB $\nu_{eq,B}$ and the inherent damping ν_I (usually 5% for r.c. structures and 2% for steel ones).

$$\nu_{eq,S+B} = \nu_{eq,S} + \nu_{eq,B} + \nu_I \tag{9}$$

In a displacement based design perspective, the performance objective is selected at first as the target displacement to meet a selected limit state for a given seismic action. The required total effective damping to make the maximum displacement less than the target one is then determined and the BRB additional damping estimated as the difference between the total damping and the hysteretic damping of the structure only. BRB characteristics are finally determined to guarantee the required additional damping. Since it usually happens that the performance point of the braced structure is different from the target one, iterations are needed until convergence.
The main steps of the procedure follow.
1. *Define the seismic action*: the seismic action is defined in terms of elastic response acceleration spectrum (T-S_a)
2. *Select the target displacement*: the target displacement is selected (for example the top displacement D_t*) according to the performance objective.
3. *Define the capacity curve*: the capacity curve of the braced structure $S+B$ in terms of top displacement and base shear (D_t-V_b) is determined by a pushover analysis. A simple modal shape load profile can be used: $\boldsymbol{\psi}=\boldsymbol{M\phi}$. Notice that the structure only S is considered at the first iteration.
4. *Define the equivalent bilinear capacity curve*: the capacity curve is approximated by a simpler bilinear curve D_t-F_{s+b} that is completely defined by the yielding point ($D_{s+b,y}$, $F_{s+b,y}$) and the hardening ratio β_{s+b} ($D_{s,y}$, $F_{s,y}$, β_s of the structure only at the first iteration).
5. *Define equivalent single degree of freedom*: MDOF system is converted in a SDOF system by transforming the capacity curve into the capacity spectrum (S_{dt}-S_{ab})

$$S_{dt} = \frac{D_t}{\Gamma \phi_t} \qquad\qquad S_{ab} = \frac{V_b}{\Gamma L} \tag{10}$$

where Γ is the participation factor of the modal shape $\boldsymbol{\phi}$ and $L=\boldsymbol{\phi}^T \boldsymbol{MI}$.

6. *Evaluate the required equivalent viscous damping*: the equivalent viscous damping $\nu^*_{eq,S+B}$ of the braced structure to make the displacement of the equivalent SDOF system equal to the target spectral displacement $S_{dt}^* = D_t^*/(\Gamma\phi_t)$ is determined. According to the Capacity Spectrum Method, this damping corresponds to a reduced demand spectra that meets the capacity spectrum at the target displacement:

$$\nu^*_{eq,S+B} \mid S_d\left(\nu^*_{eq,S+B}\right) = S^*_{dt} \tag{11}$$

7. *Evaluate the equivalent viscous damping of the structure only*: the equivalent viscous damping due to possible inelastic deformation of the structure only $\nu^*_{eq,S}$ at the target displacement is determined. Since the BRB addiction modifies the structure and then its capacity curve, $\nu^*_{eq,S}$ is evaluated as the difference between the damping of the braced structure $\nu^*_{eq,S+B}$ and the damping supplied by the BRB $\nu^*_{eq,B}$:

$$\nu^*_{eq,S} = \max\left\{\nu^*_{eq,S+B} - \nu^*_{eq,B} - \nu_I ; 0\right\} \tag{12}$$

where:

$$\nu^*_{eq,B} = \nu_{eq,B}\left(\boldsymbol{D}^*\right) = \frac{1}{4\pi}\frac{E_{D,B}\left(\boldsymbol{D}^*\right)}{E_{S,S+B}\left(D_t^*\right)} = \frac{2}{\pi}\frac{\sum_j \left(1-\beta_{bj}\right)\left(D'_{bj} - D'_{bj,y}\right)F'_{bj,y}}{D_t^* F_{s+b}\left(D_t^*\right)} \tag{13}$$

being $\boldsymbol{D}^*$ the story displacement vector at D_t^* and $E_{D,B}$ and $E_{S,S+B}$ the corresponding energy dissipated and strain energy determined from the capacity curve of the braced structure respectively. The axial displacement of the damping brace at the j^{th}-floor D'_{bj} can be determined from its inclination angle θ_{bj} and interstorey drift $\delta_j = D_j - D_{j-1}$: $D'_{bj} = \delta_j \cos\theta_{bj}$.

At the first iteration step $\nu^*_{eq,S}$ is directly given considering the structure only:

$$\nu_{eq,S} = \frac{1}{4\pi}\frac{E_{D,S}\left(D_t^*\right)}{E_{S,S}\left(D_t^*\right)} = \frac{2}{\pi}\frac{F_{sy}D_t^* - D_{sy}F_s\left(D_t^*\right)}{D_t^* F_s\left(D_t^*\right)}\kappa \tag{14}$$

where κ depends on the real structural behavior (ATC40, 1996).

8. *Evaluate the additional equivalent viscous damping*: the equivalent viscous damping needed to be supplied by the BRB to make sure that the maximum displacement of the structure with braces does not exceed the target displacement is evaluated:

$$\bar{\nu}^*_{eq,B} = \nu^*_{eq,S+B} - \nu^*_{eq,S} - \nu_I \tag{15}$$

9. *Determine BRB axial stiffness*: the BRB axial stiffness to achieve the required additional damping is evaluated. Assuming BRB with bilinear behavior at each storey:

$$\bar{\nu}^*_{eq,B} = \frac{1}{4\pi}\frac{\sum_j 4\left(1-\beta_{bj}\right)K'_{bj}\left(l_{bj}\delta_j\cos\theta_{bj} - l_{bj}^2\frac{f_{byj}}{E_b}\right)\frac{f_{byj}}{E_b}}{\frac{1}{2}\sum_j D_j F_{Sj} + \sum_j\left[\frac{f_{byj}}{2E_b}\left(1-\beta_{bj}\right)K'_{bj}l_{bj}\delta_j\cos\theta_{bj} + \frac{1}{2}\beta_{bj}K'_{bj}\delta_j^2\cos\theta_{bj}^2\right]} \tag{16}$$

where f_{byj} is the yielding strength, E_b is the elastic modulus and β_{bj} is the hardening ratio of the BRB; D_j and δ_j are the story displacement and the interstory drift at j^{th}-floor (determined from the pushover analysis at a top displacement D_t^*) respectively and l_{bj} is the BRB length at j^{th}-floor.

Select braces configuration according to architectural constraints and assembly the vector $\boldsymbol{C_b}=[c_{b1}, c_{b2}, \ldots, c_{bj}, \ldots, c_{bn}]$ that

defines BRB story stiffness distribution as given in (8). Thus, corresponding BRB axial stiffness at each floor is $\boldsymbol{K'_b}=[K'_{b1}, K'_{b2}, \ldots, K'_{bj}, \ldots, K'_{bn}]=K'_b\,\boldsymbol{C_b}$.
Assuming BRB made of the same material ($f_{byj}=f_{by}$ and $\beta_{bj}=\beta_b$) it follows from (16):

$$K'_b = \frac{\pi}{2}\frac{\overline{V}^*_{eq,B}\sum_j D_j F_{Sj}}{C_1 - C_2\overline{V}^*_{eq,B}} \tag{17}$$

where:

$$C_1 = \frac{f_{by}}{E_b}(1-\beta_b)\sum_j c_{bj}\left(l_{bj}\delta_j\cos\theta_{bj} - l_{bj}^2\frac{f_{by}}{E_b}\right) \tag{18}$$

$$C_2 = \frac{\pi f_{by}}{2E_b}(1-\beta_b)\sum_j c_{bj}l_{bj}\delta_j\cos\theta_{bj} + \frac{\pi}{2}\beta_b\sum_j c_{bj}\delta_j^2\cos\theta_{bj}^2 \tag{19}$$

10. *Check convergence*: usually, the stiffness given by (17) is not the final solution because it differs from the one used to determine the capacity curve. In this case, steps from 3 to 9 must be repeated until the top displacement meets the target one. After convergence, the BRB sections are designed.

2. CASE STUDY

The proposed design procedure is applied to retrofit an existing r.c. frame structure designed to resist vertical loads only. This structure is a 2D r.c. regular frame with three bays (5.000 m long) and three stories (2.850 m high). Beams and columns have 200×500 mm^2 and 400×200 mm^2 rectangular cross sections respectively with reinforcing arrangement shown in Figure 1. Design vertical loads, excluding self weight, include 5.00 kNm^{-2} dead loads and 2.00 kNm^{-2} live loads. The structure rises in a seismic area which is characterized by an EC8 elastic response spectrum, soil type B, with a peak ground acceleration of 0.30 g.
Structural analysis is carried out with the program code *OpenSees*: fiber non linear models are used both for frame elements and braces. In particular Kent and Park model and a modified Stanton and McNiven model have been adopted for concrete and steel materials, respectively (Figure 2 , Figure 3).

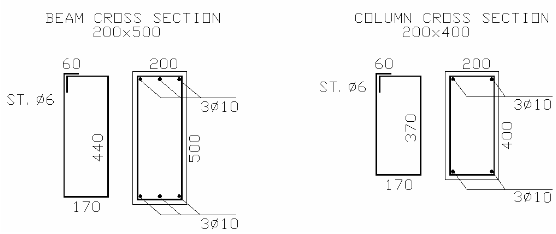

Figure 1. Details of beams (right) and columns (left) cross section.

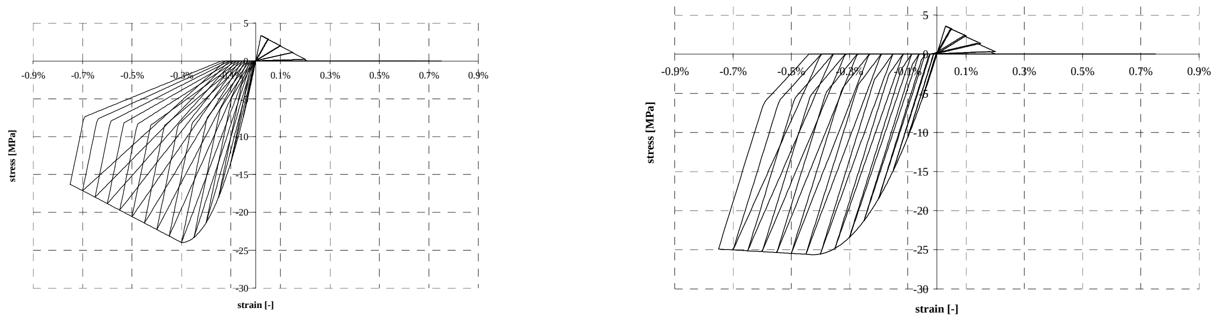

Figure 2. Cyclic model of unconfined and confined concrete.

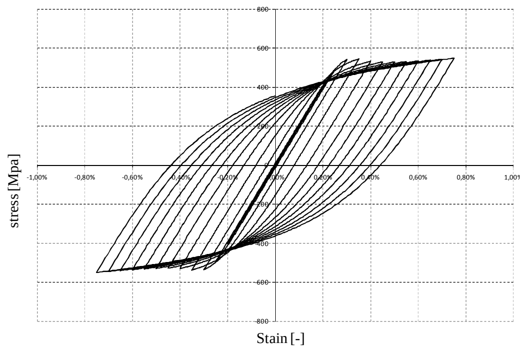

Figure 3. Cyclic model of the reinforcing steel.

According to the proposed approach, pushover analyses have been carried out to define the capacity curves and to evaluate the structural response of both existing and braced frame. First mode proportional load profiles have been applied but it is worth noticing that different kinds of pushover methods (e.g. multimodal or adaptive) could be used as well if considered more suitable for the purpose without any changes in the procedure.
The Capacity Spectrum Method is used to predict the performance point of the structure and then to evaluate its corresponding seismic response in terms of horizontal story displacements and damage distribution.
The performance point of the existing structure in terms of base shear and top displacement is V_b=227 kN and D_t=50 mm and, as shown in Figure 5(a), the structure has a shear type deformation and is heavily damaged with plastic hinges spreading mainly at the ends of the lower columns.
Then, the performance objective is to reduce maximum displacements so as to avoid structural damage in case of a 0.30 g seismic event.
A target top displacement equal to 25 mm is selected: this value is about 50% less than the maximum top displacement of the existing frame and about 3‰ of the total height of the frame, then it is assumed to be the target displacement to meet a serviceability limit state.
BRB configuration has been chosen according to architectural constraints and devices designed for the selected performance objective.

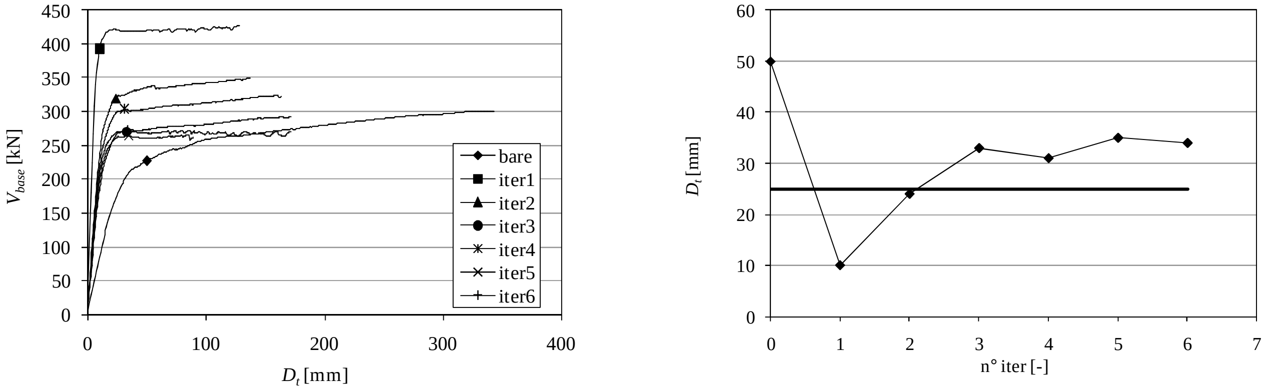

Figure 3. (a) BRB effect on capacity curves, (b) Performance top displacement of the braced frame at each step (iter=0 is the original frame).

As shown in Figure 3(a), BRB addition modifies the capacity curve of the existing frame and thus its performance point. The iterative procedure converges quickly to the target displacement as depicted in Figure 3(b).
The performance point of the braced frame with BRB designed at step 2 is defined by a base shear V_b=319 kN and a top displacement D_t=24 mm (practically coincident with the target one).
Non linear dynamic analyses have been performed to assess the effectiveness of the proposed procedure.
Twenty-one natural earthquakes on different soil types and different peak ground accelerations have been selected

to perform incremental non linear dynamic analyses. Results in terms of capacity curves are shown in Figure 4. Notice that BRB addition makes the deformation of the frame much more sensitive to the fundamental mode of vibration so that pushover analysis results become much more effective.

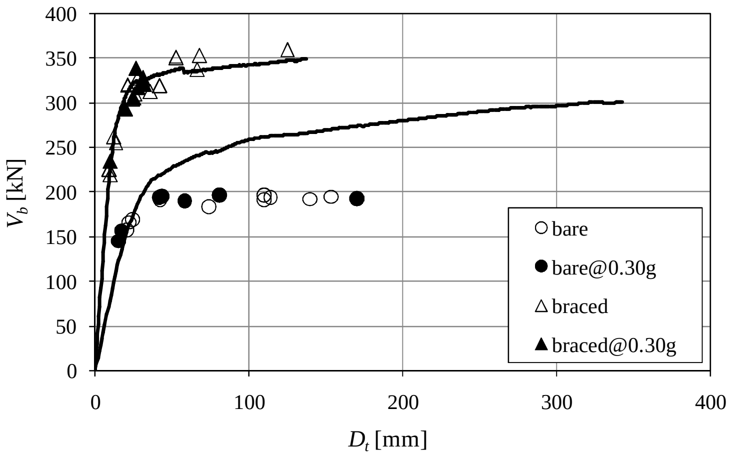

Figure 4. Capacity curves vs. incremental nonlinear dynamic analyses of bare and braced frame.

The mean maximum base shear and top displacement from dynamic analyses with pga=0.30 g are equal to 181 kN and 61 mm for the bare frame and 305 kN and 25 mm for the braced one which are in a very good agreement with the ones estimated by means of the Capacity Spectrum Method and in particular with the target top displacement. As shown in Figure 5, the addition of BRB significantly reduces damages with respect to the original frame: at the target displacement all BRB are yielded and dissipate energy enough to make the braced frame able to survive a 0.30 g earthquake almost with no structural damages. So, BRB allows retrofitting of the original structure.

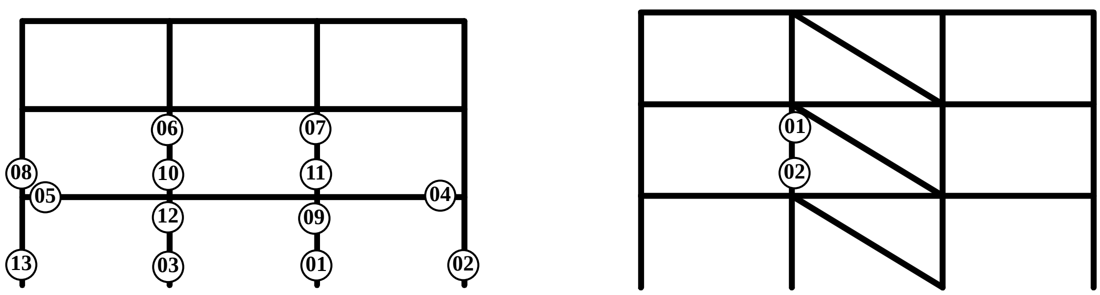

Figure 5. Damage distributions of existing and retrofitted frame.

Other examples on 2D and 3D frame structures are given in (Albanesi et al., 2007a, 2007b, 2008).

REFERENCES

Albanesi, T., Bergami, A.V., Nuti, C. (2007a). Protezione sismica di telai tamponati mediante controventi dissipativi. *XII Convegno Nazionale - L'Ingegneria Sismica in Italia*, ANIDIS, Pisa, Italy, June 10-14, 2007.

Albanesi, T., Bergami, A.V., Nuti, C. (2007b). Displacement-based design of buckling-restrained braces for the seismic rehabilitation of existing r.c. frames. *10th World Conference on Seismic Isolation, Energy Dissipation and Active Vibrations Control of Structures*, ASSISi, Istanbul, Turchia, 28-31.05.2007.

Albanesi, T., Bergami, A.V., Nuti, C. (2008). Displacement based design of BRB for the seismic protection of r.c. frames. *International Official FIB Symposium "Tailor Made Concrete Structures – New Solutions for Our Society"*.

Amsterdam, The Netherlands, May 19-22, 2008.

Applied Technology Council. (1996). Seismic evaluation and retrofit of concrete buildings. *Report ATC-40*, Redwood City, California.

Kim J., Choi H. (2004). Behavior and design of structures with buckling-restrained braces. *Engineering Structures*, **26**: 693-706.

Silvia Mazzoni, Frank McKenna, Michael H. Scott, Gregory L. Fenves, et al.. OpenSees Command Language Manual

Zhang R.H., Soong T.T. (1992). Seismic design of viscoelastic dampers for structural applications. ASCE, *J. of Structural Engineering*, **118(5)**: 1375-1392.