Assessment of Seismic Behavior of 3D Asymmetric Steel Buildings Retrofitted with TADAS Device Based on Incremental Dynamic Analysis (IDA)

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SUMMARY:
Control of structure response versus ground motion is one of important issues in earthquake engineering. Various solutions and devices have been innovated for this purpose so far. One of these devices is metallic yielding dampers. In this article, triangular shaped yielding dampers, well-known as TADAS, have been considered. For further discussion, this damper is installed on a steel structure that has been modeled as 3D and then is subjected to 40 strong ground motions. For structure analysis, OPENSEES program is used. Through analyzing the obtained results, IDA surfaces are generated. Then advantages and disadvantages of using these dampers will be introduced. Finally, a pattern for improvement of system performance has been proposed.

Keywords: Passive Control – TADAS Dampers – 3D Steel Structure – IDA - OPENSEES

1. INTRODUCTION

Nowadays, using of dampers for control of structure response versus earthquake is spread widely. This manifests itself, in creation of various dampers and structure control devices such as active, semi-active and passive. Among those, metallic yielding dampers (see Fig.2.1) for relative advantages are one of the most interesting ones. These advantages are such as: 1. Increase in damping and ductility of structure and reduction of displacement, 2. Concentration of damages due to energy dissipation in this device, without interference in transition path of vertical loads, 3.Fruition of fully stable hysteresis loops with minimum deterioration of stiffness and strength, 4. Obviates of maintenance and technical inspection, 5.Ease in device replacement by bolt connections.

Among metallic yielding dampers, triangular shape types have some advantages respect to other types of those. In this type, due to the triangular shape, in case of any displacement at the end of the plate, where pin joint connection has occurred, moment curvature is distributed uniformly in plate height and consequently, moment stress is uniform in the entire plate. It signifies an optimal use of material. [Tsai and Chen, 1993] In the following, the governing equations of behavior of these dampers have been represented.

2. GOVERNING EQUATIONS OF TADAS BEHAVIOR

Supposing the connections between triangular plates with beam are moment resistant and the plate is pinned with braces, regardless of shear deformations, elastic lateral stiffness of TADAS device is obtained according to Eqn.2.1.

$$K_d = \frac{NEbt^3}{6h^3} \tag{2.1}$$

In which, E is Young module, N is number of plates, t is thickness of plates and b and h are, respectively, the width and the height of the triangular plates. Curvature of section due to moment and section geometric characteristics is independent of height of section, therefore, is uniform on entire of section height (see Fig.2.2):

$$\psi_y = \frac{M(y)}{EI(y)} = \frac{F \times y}{Ebyt^3 / 12h} = \frac{12Fh}{Ebt^3} = cons. \tag{2.2}$$

$$\Delta = \frac{\psi h^2}{2} \tag{2.3}$$

Therefore, the force-displacement relationship for one of the plates is Eqn.2.4:

$$F = \left(\frac{Ebt^3}{6h^3}\right)\Delta \tag{2.4}$$

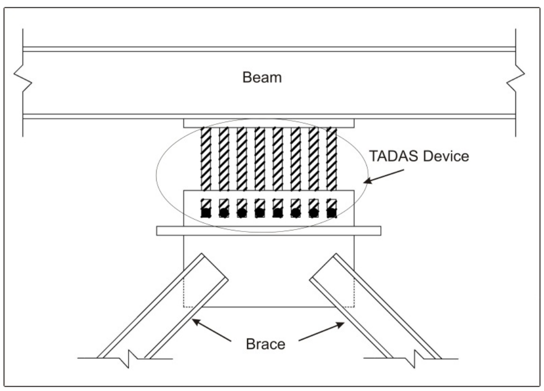

Figure 2.1.TADAS Device & Brace

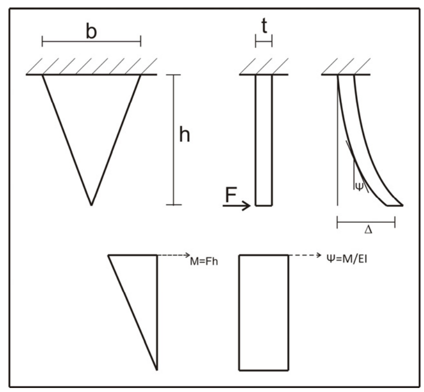

Figure 2.2.Moment Curvature Diagrams

In which, ψ is curvature of section but above equations can represent elastic behavior only. Researches on finite element models has shown that if steel stress-strain curve is supposed to be ideal elastic-plastic and bilinear, with consideration of 5 percent strain hardening, it could reach to high accuracy. [Tsai and Chen, 1993]

3. DESIGN METHODS OF FRAME WITH TADAS DAMPERS

3.1. Characteristics of Damper

To illustrate, TADAS element consists of TADAS device and two braces that support it and TADAS frame is a frame with TADAS element. Lateral stiffness of element (K_a) is a function of braces stiffness (K_b) and device stiffness (K_d) .If the ratio of lateral element stiffness (K_a) to frame stiffness without damper (K_f) is SR (Eqn3.1), then we have:

$$SR = \frac{K_a}{K_f} \tag{3.1}$$

$$K_a = \frac{K_b K_d}{K_b + K_d} \quad (3.2)$$

Because, yielding of TADAS device generally happens before frame enters into the nonlinear regime, force-displacement relationship of frame could be considered as tri-linear model. In Fig.3.1, TADAS frame elastic stiffness is:

$$K_s = K_a + K_f \quad (3.3)$$

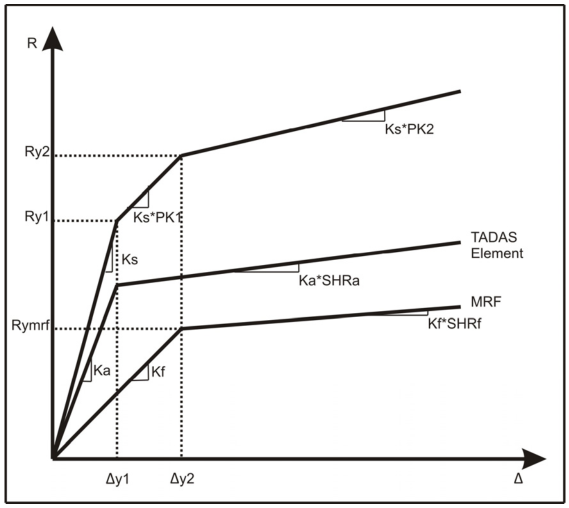

Figure 3.1. Tri-Linear Force-Displacement Relationship of Frame with TADAS element

Δ_{y1}, Δ_{y2}, are respectively, yield displacement of TADAS element and yield displacement of frame without the element. R_{y1}, R_{y2}, are applied forces to system whenever it reaches at yielding displacements Δ_{y1}, Δ_{y2}. SHR_A is ratio of stiffness after yielding and K_a is initial stiffness of element, therefore element stiffness after yielding is $K_a \times SHR_A$,also:

$$U = \frac{R_{y2}}{R_{y1}} \quad (3.4)$$

With above equations, basic equation of damper is Eqn.3.5:

$$\frac{\Delta_{y2}}{\Delta_{y1}} = 1 + \frac{1 + SR}{1 + SR \times SHR_A}(U - 1) \quad (3.5)$$

3.2. Effective Parameters in Design

Among 3 parameters SR, Δ_y, U; 2 parameters is independent and the third parameter is calculated according to Eqn3.5.Test results indicated that ductility factor of TADAS element is sensitive with respects to Δ_y and a smaller Δ_y is suitable. [Whittaker and Bereero, 1989] But this parameter must be large enough to prevent large ductility ratios in element.SR parameter is ratio of initial stiffness of element and frame stiffness. This ratio is very important in structure design, because it depends directly on structural element stiffness and consequently, it influences periods and design forces of structure. Large values of SR cause a reduction in displacements and an increase in the input energy into structure.

Choosing the suitable SR value is depended on earthquake characteristics and intensity, structure periods and dissipation energy capacity into account. Choosing a large value for SR does not essentially imply a better design because that would decrease the characteristic period of the structure and this might result into a surge in the response accelerations and shear forces of structure in addition to an increase in size and cost of element, as a value within a range of 2-4 is mostly recommended. [Whittaker and Bereero, 1989]

Studies suggest that U=2, is almost optimal, however, it is almost impossible to achieve greater quantities of U, in practice. Hence, we mainly focus on changing SR in the present study, since, this parameter is of magnificent interest and easy to manipulate at the same time. Another parameter is Kb/Kd (or B/D) which plays a role as it is described in the below:

$$K_a = \frac{K_b K_d}{K_b + K_d} = \frac{K_d}{1 + \frac{1}{K_b / K_d}} \qquad (3.6)$$

$$\alpha = \frac{1}{1 + 1/(B/D)} \qquad (3.7)$$

$$K_a = \alpha K_d \qquad (3.8)$$

From Eqn.3.6, it can be deduced that with an increase in B/D from 1 to 5, α rises rapidly, whereas for B/D surging beyond 5 up to 100, α increases rather slowly which, ultimately, reaches its limit of 1. Changes in B/D has little impact on reducing the structural response during earthquakes. Bracing members should be designed, exclusively, in a way that they maintain their elasticity during the earthquake does not buckle. B/D ratio influences deformation of TADAS element before yielding. After yielding, element stiffness due to inelastic deformations decreases regardless of braces stiffness. Therefore, a B/D between 2 to 3 is recommended.

4. CHOOSING SR VALUE

In advance of considering IDA, to select the best SR value, a non-linear analysis is used. For this purpose, two sets of 3 ground motion, one for hard soil and soft soil is taken. The structure is modeled in OPENSEES software and for beam and column elements modeling *Beam with Hinges* element is applied so that there would exist a capability of forming plastic joints at the ends. Also bilinear material is used. The bilinear material model an extension to the basic elastic-plastic hardening formulation, with additional features to model softening at large deformation and hysteretic deterioration.[Altoontash ,2004, Ibarra and Ricardo,2005]

The structure without dampers and 3 structures with 3 different SR of values 2&3, 4 have been generated. Elastic stiffness and yield displacements have been calculated from pushover curves of each floor. As soon as these two parameters are known, damper characteristics will be calculated easily.

Table 1. Periods of Structure with and without dampers

Periods(second)	Structure Without Damper	Structure with Damper SR=2	Structure with Damper SR=3	Structure with Damper SR=4
1st mode (X Dir)	1.96	1.21	1.12	1.04
2nd mode (Z Dir)	1.82	1.137	1.04	0.97

It is noticeable that, SR=4 is more effective in reduction of story displacement and acceleration for rock soil site than others in general. SR=2 is more effective in reducing the story shear, especially base shear, for rock soil site than others, on the whole. Cases 1 and 2 are almost true for soft soil site but in higher stories, acceleration for structure with damper is more than the one without the damper.

The results are consistent with Tsai recommendation [Tsai and Chen, 1993], which indicated that SR=2 was more effective for long period structures and SR=4 for short period ones, since the 1st period of the structure has 1.96s, it is considered a long-period one and as it is expected SR=2 has provided the best desired response.

5. INCREMENTAL DYNAMIC ANALYSIS

Incremental dynamic analysis (IDA) is a method, in which, through consecutive non-linear dynamics analysis subjected to several scaled ground motion records, the ability to predict the seismic capacity and demands is gained. To realize this, one needs to choose, appropriately, values of parameters, such as intensity measure (IM) of ground motions and damage measure (DM).Moreover, interpolation methods for estimating the seismic capacity is needed.[Vamvatsikos and Cornell, 2002]

5.1. Intensity Measure (IM)

Peak ground acceleration (PGA) and response acceleration (Sa(T,ξ)) are the most basic parameters for intensity measure. A suitable IM as far as possible must not depend on earthquake records, but these parameters, especially PGA, depend on record mostly. The elastic acceleration response cannot be an appropriate IM, because this parameter will not be representative of non-linear behavior such as stiffness and strength deterioration. So there were two-parameter criteria to include non-linear behavior as well. This parameter is less sensitive to the earthquake record.it is as combination of two periods and considering the interval for changing period of structural due to non-linear behavior under severe earthquake. Here β , c parameters have been calculated by statistical process in general case. [Vamvatsikos and Cornell, 2005, Cordova, Deierlein, Mehanny and Cornell]

$$IM = S_a(T_1,\xi)^{1-\beta} \times S_a(cT_1,\xi)^{\beta} \tag{5.1}$$

$$c = 2, \beta = 0.5$$

5.2. Damage Measure (DM)

Numerical values of the damage index are positive, indicating that the response is a structure against seismic loads. In other words, a DM value is a calculated value that can indicate response of structure in dynamics analysis. In this article, *Mehanny & Deierlein (2000)* Damage measure is used. This model is based on cumulative deformations of elements in a form of total plastic deformations. The damage benchmark is of the damage model based on the energy developed by *Kratzing* and inspired by *Otes* work on capturing the cyclic damage. This model includes the maximum amounts of plastic positive and negative deformations and α, β, γ parameters are used for calibration. Plastic rotation θ_p is used as basic input for damage model. The plastic rotation is supplied to the damage model either in form of a pure plastic deformation or as the non-recoverable part of the elastic deformation calculated from the total deformation, force and unloading stiffness, using the following Eqn.5.2:[Mehanny and Deierlein, 2001, Altoontash ,2004]

$$\theta_p = \theta_{total} - \frac{F}{K_{unloading}} \tag{5.2}$$

A half cycle is defined as a monotonic change in plastic deformation. Once the plastic deformation increment $\delta\theta_p$ changes direction, a new half cycle is initiated. To eliminate unnecessary cycles, all the excursions smaller than certain limits are filtered out. The primary Half Cycle (PHC) refers to the half cycle either highest magnitude, while any other half cycles with smaller amplitude are referred as a Follower Half Cycle (FHC). The definition of PHC is slightly different than the definition used for

Kratzing model.in this formation there is a unique PHC at each point and once a new PHC occurs the former PHC will be treated as a FHC.

$$DI^{\pm} = \frac{(\theta_p^{\pm}|_{currentPHC})^{\alpha} + (\sum \theta_p^{\pm}|_{FHC,i})^{\beta}}{(\theta_{pu}^{\pm})^{\alpha} + (\sum \theta_p^{\pm}|_{FHC,i})^{\beta}} \tag{5.3}$$

$$DI = \sqrt[\gamma]{(DI^{+})^{\gamma} + (DI^{-})^{\gamma}} \leq 1.0 \tag{5.4}$$

This damage model has some Specifications: 1. Calculate Cumulative damage, 2. Reflect the transient effects of structural loading, 3. Suitable for the asymmetric behavior of composite beams.

5.3. Used Ground Motion Records

Table 2. Ground Motions Set

Record number	NGA Record Sequence Number	Earthquake Name	Year	Station	Magnitude	Closest Distance	Preferred Vs30 (m/s)
1	72	San Fernando	1971	Lake Hughes #4	6.6	25.1	822
2	769	Loma Prieta	1989	Gilroy Array #6	6.9	18.3	663
3	1165	Kocaeli, Turkey	1999	Izmit	7.5	7.2	811
4	1011	Northridge-01	1994	LA - Wonderland Ave	6.7	20.3	1223
5	164	Imperial Valley-06	1979	Cerro Prieto	6.5	15.2	660
6	1787	Hector Mine	1999	Hector	7.1	11.7	685
7	80	San Fernando	1971	Pasadena - Old Seismo Lab	6.6	21.5	969
8	1618	Duzce, Turkey	1999	Lamont 531	7.1	8	660
9	1786	Hector Mine	1999	Heart Bar State Park	7.1	61.2	685
10	1551	Chi-Chi, Taiwan	1999	TCU138	7.6	9.8	653
11	3507	Chi-Chi, Taiwan-06	1999	TCU129	6.3	24.8	664
12	150	Coyote Lake	1979	Gilroy Array #6	5.7	3.1	663
13	572	Taiwan SMART1(45)	1986	SMART1 E02	7.3	-	660
14	285	Irpinia, Italy-01	1980	Bagnoli Irpinio	6.9	8.2	1000
15	801	Loma Prieta	1989	San Jose - Santa Teresa Hills	6.9	14.7	672
16	286	Irpinia, Italy-01	1980	Bisaccia	6.9	21.3	1000
17	1485	Chi-Chi, Taiwan	1999	TCU045	7.6	26	705
18	1161	Kocaeli, Turkey	1999	Gebze	7.5	10.9	792
19	1050	Northridge-01	1994	Pacoima Dam (downstr)	6.7	7	2016
20	2107	Denali, Alaska	2002	Carlo (temp)	7.9	50.9	964
21	1	Helena, Montana-01	1935	Carroll College	6	-	660
22	1091	Northridge-01	1994	Vasquez Rocks Park	6.7	23.6	996
23	1596	Chi-Chi, Taiwan	1999	WNT	7.6	1.8	664
24	771	Loma Prieta	1989	Golden Gate Bridge	6.9	79.8	642
25	809	Loma Prieta	1989	UCSC	6.9	18.5	714
26	265	Victoria, Mexico	1980	Cerro Prieto	6.3	14.4	660
27	1078	Northridge-01	1994	Santa Susana Ground	6.7	16.7	715
28	763	Loma Prieta	1989	Gilroy - Gavilan Coll.	6.9	10	730
29	1619	Duzce, Turkey	1999	Mudurnu	7.1	34.3	660
30	957	Northridge-01	1994	Burbank - Howard Rd.	6.7	16.9	822
31	2661	Chi-Chi, Taiwan-03	1999	TCU138	6.2	22.2	653
32	3509	Chi-Chi, Taiwan-06	1999	TCU138	6.3	33.6	653
33	810	Loma Prieta	1989	UCSC Lick Observatory	6.9	18.4	714
34	765	Loma Prieta	1989	Gilroy Array #1	6.9	9.6	1428
35	1013	Northridge-01	1994	LA Dam	6.7	5.9	629
36	1012	Northridge-01	1994	LA 0	6.7	19.1	706
37	1626	Sitka, Alaska	1972	Sitka Observatory	7.7	34.6	660
38	989	Northridge-01	1994	LA - Chalon Rd	6.7	20.5	740
39	748	Loma Prieta	1989	Belmont – Envirotech	6.9	44.1	628
40	1549	Chi-Chi, Taiwan	1999	TCU129	7.6	1.8	664

This ground motion set consists of 40 unscaled three component ground motion selected so that their response spectra math the median and log standard deviations predicted for a magnitude 7 earthquake at a distance of 10 km .The Vs30 was assumed to be 760 m/s. all ground motions in the database with Vs30>625 m/s were considered for inclusion in the set. Therefore this set consists of rock site earthquake records generally.[Baker, 2011] Should be noted that the rock site records Since are applied in the structures often in short time, damper effects on reducing the structural response is less and since the change of period is from long to medium period, in this type of records input acceleration has significant increase generally and could say the most difficult conditions for structure is considered.it is expected that the impact of adding the damper to structures be more effective in soft soil records.

6. PERFORMING ANALYSIS AND RESULTS

After preparing the necessaries of IDA, analysis is performed. Structure without damper and structure with damper (with SR=2) are subjected to 40 ground motion records that have been scaled by given IM. analysis is initialed in low IM value and will go to high value of it.in each analysis the value of DM for all members are recorded and in each floor value of total damage is calculated from Eqn.5.1.

$$DI_f = \frac{\sum_{i=1}^{n} DI^2}{\sum_{i=1}^{n} DI} \tag{5.1}$$

In Eqn5.1, *n* is number of members that their DMs have been considered to reach total DM of floor. After calculating the DM values of each floors, to consider all DMs of floor to reach total DM of structure, average plus standard deviation of them (84%) is used. IDA surfaces have been shown in Fig.6.1 & Fig.6.2. Two horizontal vectors are IM in Z direction of structure and ratio of IMx/IMz and vertical vector is total DM of structure.

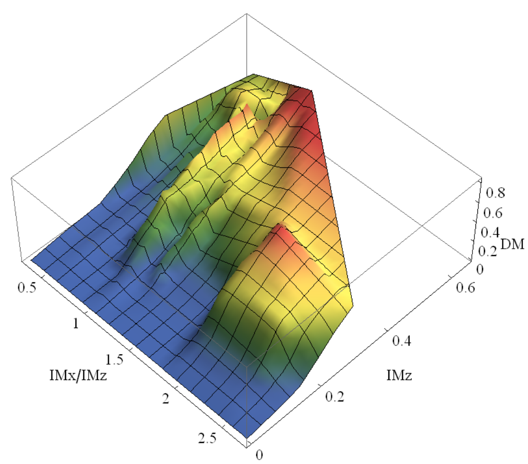

Figure 6.1.IDA Surface, Structure without dampers

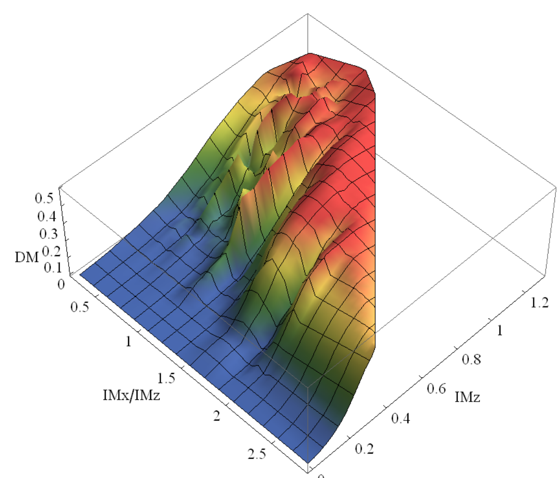

Figure 6.2.IDA Surface, Structure with Damper, Uniform Distribution

In Fig 6.1 & Fig 6.2, IDA surfaces have been shown respectively for structure without damper and structure with damper.in these figures, vertical axis is total damage of structure and horizontal axises are intensity measure in Z direction (IMz) and ratio of IMz/IMx. In comparison of Fig 6.1 & Fig 6.2, it is clear that damage measure has been decrease in structure with damper although intensity measure has been increase. In addition, response of structure with dampers, subjected to ground motions, is more predictable than structure without dampers, which represents a reduction of non-linear behavior and structural damage. On the other hand, when ratio of IMx/IMz has increased, value of intensity measure has decreased; this could mean that the structure in X direction is weaker than Z direction.

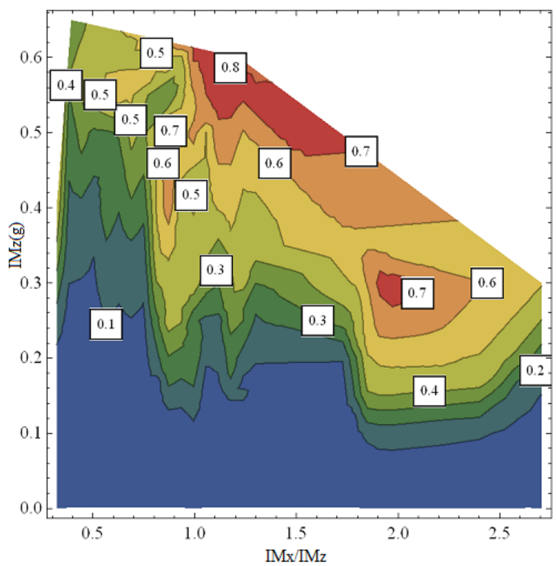

Figure 6.3.IDA Contour, Structure without damper

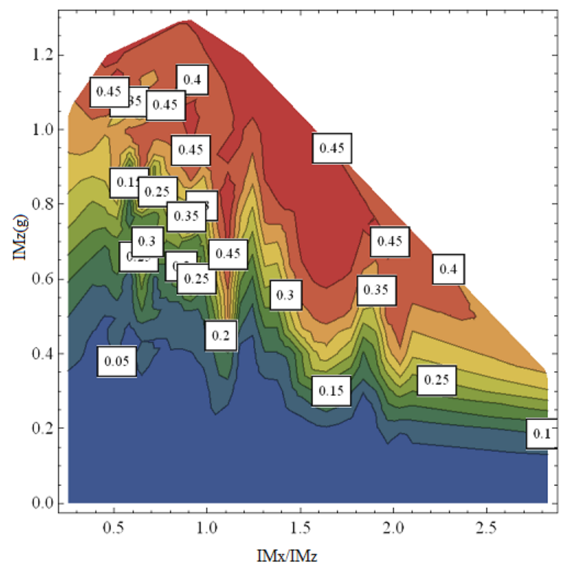

Figure 6.4.IDA Contour, Structure with Damper, Uniform Distribution

The contour of damage measure has been shown in Fig 6.3 & Fig 6.4 respectively for structure without damper and structure with damper.in these figures vertical axis is IMz and horizontal axis is IMx/IMz ratio.

7. PROPOSED DISTRIBUTION

It was talking about how to choose SR value but this question had been exist that why this parameter should be considered the same for all stories? Since that one effect of increase in this value causes to increase in stiffness of structure and resulting in reduction of displacement, it is seemed that could use where more need of its. But as was said, increase in this parameter for all classes has no scientific and economic justification always. So tried to with minimal changes in existing conditions, in terms of material and structural parameters a more appropriate distribution is considered. Distribution characteristic is that the value of average SR is determinable only its distribution is variable in height. It is important that the value of average SR is specified so Tsai criteria [Tsai and Chen, 1993] could use for selection SR value. The criterion was based on structural period. From Eqn.7.1, SR_{in} for each floor calculates. This equation expresses that for story has minimum yield displacement, value of SR must be greater than other stories and with increase SR value, R_y increases for story with less yield displacement.

$$SR_{in} = \frac{2 - \dfrac{\Delta_{yi}}{\Delta_{y\max}}}{2 - \dfrac{\Delta_{y\min}}{\Delta_{y\max}}} \tag{7.1}$$

Then an average value for the SR should be considered that Here is called SR_c and It can be selected according to Tsai's recommendations [Tsai and Chen, 1993] .According to the period of structure is considered SR=2. So we will:

$$SR_c = \frac{\alpha \sum SR_{in}}{n} \tag{7.2}$$

In Eqn.7.2 , n is number of stories and α is a constant factor that it is weight for average actually, This value is obtained using the following equation that Its parameters has been known previously.

$$\alpha = \frac{n \times SR_c}{\sum SR_{in}} \tag{7.3}$$

After calculation of α parameter, by multiplying it to SR_{in} the amount SR_i of each story is calculated:

$$SR_i = \alpha \times SR_{in} \tag{7.4}$$

We will evaluate the structure again with this difference that can be tried by using the above explanations could be achieved better results. In fact, one of the goals that are pursued in this section it can be shown that carefully designed damper is a way that is appropriate to structure will most benefit from the damper advantages.

Table 3. Periods of Structure with Damper SR=2 uniform and Proposed Distribution

Periods(second)	Structure Without Damper	Structure with Damper SR=2 uniform	Structure with Damper SR=2 Proposed Distribution
1^{st} mode (X Dir)	1.96	1.21	1.2
2^{nd} mode (Z Dir)	1.82	1.137	1.135

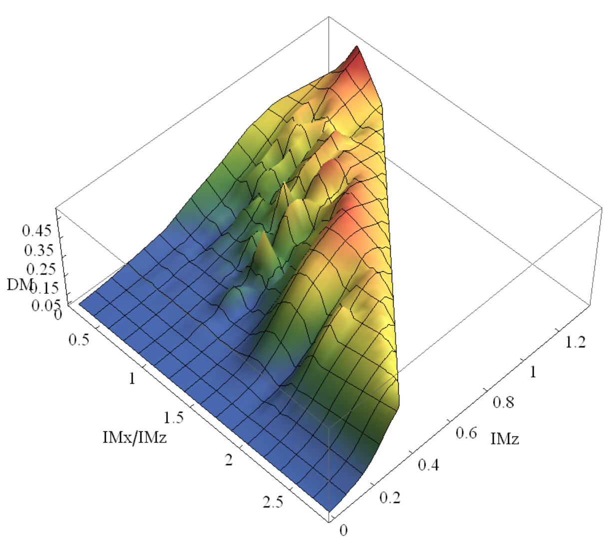

Figure 7.1.IDA Surface, Structure with Damper, Proposed Distribution

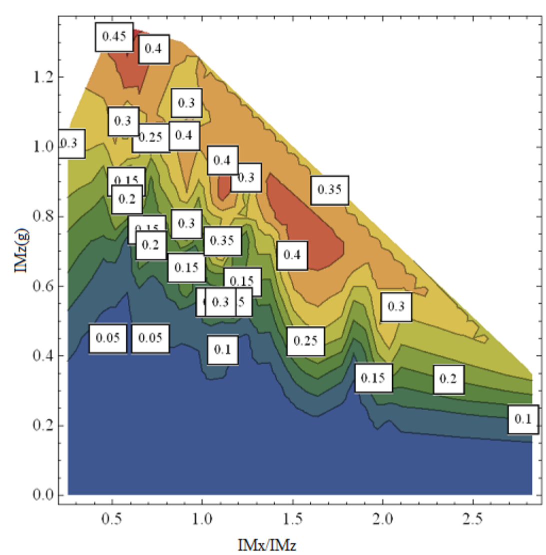

Figure 7.2.IDA Contour, Structure with Damper, Proposed Distribution

8. CONCLUSIONS

Metallic dampers that have a variety of types, placement in structures and performance, can be most useful and the simplest type of damper, in terms of analysis and design will be considered. Between different types of metallic dampers, the triangular shape that it is known TADAS, have some advantages than other types of them that they noted, but every device can have disadvantages, hence can be useful to address these issues in this section. Given all the advantages mentioned in this study, it should be noted, this damper on the nature increases stiffness of the structural system, becoming stiffer structures will behave differently depending on the type of structure. Structures with short periods being stiffer the acceleration is usually decreased. While for a long period is usually associated with increasing acceleration and about the middle period, both are likely. So, using this damper requires caution. To add to all afore-mentioned characteristics of structure and its period, soil type, also, is of profound importance in the earthquake record and, consequently, the response spectrum. Therefore, one should act in a way that the aacceleration changes in a controlled fashion, which is feasible, only up to a limited extent.

It can be deduced that by adding the damper and its bracing, frame stiffness and resistance is increased. So using this damper can be beneficial for weak and soft story. By using the proposed distribution, automatically there will be added more stiffness to the story that yields in smaller displacement and thus the weak story problem can be dealt with properly. This is also true about the soft story but, since a soft story, generally, has a greater height than other ones, some considerations need to be taken into account to prevent braces from buckling.

Finally, we can conclude that the metallic damper, despite some disadvantages can be effective in reducing structural response. But above all, one must always consider the above mentioned factors, in the analysis and design so that the final design is appropriate, useful and the economically efficient enough.

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