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Optimized Design Ratio of Frame Part Participation in Walled-Framed System of R\C Building

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Abstract:

Buildings that are designed with seismic resistant dual shear walled – framed systems are required to fulfil the 25% minimum design lateral force resistance ratio for the frame part alone (without the contribution of the shear walls). This condition raises the question that what is the resulting ratio for the design lateral resistance of the frame part in dual system if an artificial intelligence algorithm was used in the designing process. For this purpose, a dual shear walled- framed system of three spans and five stories is analytically verified to have the nearest possible results to an experimental test by Devi, G. N. (2013). Then an optimum design for the same system is performed. A heuristic algorithm with two phase design variables is used in the optimized design. These variables are prepared at first to be suitably few for the search algorithm to be cost effective in the manner of time needed to have results. This is called phase-1 optimization. Then the number of variables is expanded to cover all the design aspects in the model in phase-2 while using the results of phase-1 as initial values of phase-2. The cost-based optimum design's objective function takes into consideration the cost of building materials used (concrete and steel) and the cost of square meter of the formwork used to shape members during curing process. The cost of any section is estimated for unit length of member, then the total cost of the whole system is calculated by summing up the cost of all members. In this research an FEM nonlinear program used for analysis (Abaqus) and Python package for machine learning and optimization is used in the optimization process. The frame part participation ratio resulted, though exclusive to the system considered in this research, it ignites the curiosity to investigate several dual system configurations of R\C buildings that could be considered in future works.

Keywords: Dual Systems, Seismic Shear Resistance Ratio, Optimized Design, Heuristic Algorithm, Design Variables.

Shearالنسبة المبنية على التصميم الأمثل لمساهمة الجزء الإطاري في الجمل الثنائية جدران قص-إطارات في الأبنية الخرسانية المسلحة

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الملخص:

إن الأبنية المصممة لمقاومة الزلازل ذات الجمل الثنائية جدران قص-إطارات يجب أن تحقق مقاومة تصميمية لقوى القص القاعدي لا تقل عن 25% للجزء الإطاري وحده (بدون مساهمة جدران القص). هذا الشرط يثير التساؤل عن ماهية هذه النسبة أي كيف ستكون قيمتها فعلياً في حال تم الإستعانة بخوارزمية ذكاء صنعي للوصول إلى التصميم الأمثل لمثل هذا البناء. من أجل هذا الهدف وقع الإختيار على نظام إنشائي مكون من ثلاث فتحات ويرتفع إلى خمسة طوابق ليتم تحليله حاسوبياً والتأكد أولاً من مقاربة النتائج التحليلية للنتائج المخبرية التي صدرت عن هذه الجملة التي أجريت عليها تجارب مخبرية من قبل Devi, G. N. (2013). ومن ثم تمت إعادة تصميم هذه الجملة بالشكل الأمثل وفق خوارزمية أمثلة مع اعتبار متحولات التصميم مختلفة ضمن مرحلتي أمثلة متتابعتين. حيث تم تحضير المتحولات في البداية لتكون بالعدد الأقل الممكن من أجل تمكين خوارزمية الأمثلة من إيجاد التصميم الأمثل الأولي بالكلفة التحليلية الأقل بالنسبة للوقت المستهلك للوصول لتلك النتائج الأولية. وقد أطلق على هذه المرحلة بالأمثلة الأولى Phase-1. ثم بعد ذلك تم توسيع عدد المتحولات لتشمل جميع جوانب التصميم الخاصة بالنظام الإنشائي بمرحلة الأمثلة الثانية Phase-2 والتي اتخذت من نتائج Phase-1 كقيم ابتدائية لإطلاقها. بني التصميم الأمثل على كلفة النظام الإنشائي كتابع هدف يأخذ بعين الإعتبار كلفة مواد البناء المستخدمة (خرسانة و فولاذ) بالإضافة إلى كلفة المتر المربع من القالب المستخدم لتشكيل العناصر الخرسانية المسلحة خلال فترة التصلب. إن كلفة أي مقطع إنشائي تم تقييمها ككلفة واحدة الطول من العنصر الإنشائي، بحيث يمكن الحصول على الكلفة الكلية لكامل النظام الإنشائي بعد حساب مجاميع كلفة جميع العناصر (ضرب طول كل عنصر بكلفة المتر الطولي للمقطع منه). من أجل ذلك تم في هذا البحث تم استخدام برنامج Abaqus كبرنامج يعتمد اللاخطية في تحليل المنشآت بطريقة العناصر المحدودة خلال عملية الأمثلة. كنتيجة صدرت عن هذا البحث فإن نسبة مشاركة الجزء الإطاري من النظام الإنشائي رغم أنها حصرية للنظام الإنشائي المعتمد في هذا البحث حصراً، إلا أنها تثير الفضول لمعرفة كيفية تغير هذه النسبة في كل مرة يعمد فيها إلى تغيير المسقط الأفقي وتوزع الجدران فيه أي اعتماد ترتيبات لمسقط أفقي مختلفة في بناء خرساني مسلح وهو ما سيصدر في أعمال بحثية مستقبلية.

الكلمات المفتاحية: النظام الثنائي، نسبة المساهمة القصية الزلزالية، التصميم الأمثل، الخوارزمية التجريبية، متحولات التصميم.

Introduction:

During damaging earthquakes buildings are subjected to extreme loads initiated by inertia forces, the results of rapid movement of the structure. For design purposes inertia forces are equated by a static system of lateral seismic forces affecting the structural system of the building from top to bottom. In dual shear wall-frame seismic resisting structural systems shear walls are considerably stiffer than frames therefore they are first affected by the seismic loads followed by the framework system of the structure. Shear walls should have the adequate rigidity and strength to withstand the seismic action on the building, especially in the lower stories of the building. Whereas frames are not as rigid and may develop larger deformations before reaching plastic hinge development when compared to shear wall system. The codes of design imposes at least 25% design strength ratio required to be on the frames part of the structure to compensate for the loss of strength that may occur after a strong seismic event that could cause damage to shear walls. This role of frame part is crucial for supporting vertical loads of a building. Design guidelines and codes don't give a specific ratio in order to guarantee a better performance and/or economic design, only a minimum ratio of 25%. Therefore, an optimum design of a dual system may yield a suitable ratio, or at least a range of ratios that could be recommended for better performance and/or economic design for the dual shear wall frame systems. This design should fulfill all the requirements and provisions of codes with a minimum cost of construction. Previously, close to this purpose included the seismic design of seismic resistant shear walled-building and their performance Wallace (1995a and 1995b), Sasani (1998). In 2001 Kowalsky introduced displacement-based methods to design shear walls according to the UBC. All these studies were considered in the optimum design of RC buildings because they've introduced the main conditions and provisions of the seismic design. For this Saka (1991) considered displacement, ultimate axial load and bending moment with limitation on dimensions and performed optimization to control sway. Fadaee and Grierson (1998) performed optimum design on R\C buildings having shear walls. In addition, Camp et. al. (2003), Lee and Ahn (2003) developed a procedure to design reinforced concrete frames using a genetic algorithm. Camp et. al. used ACI code to put main requirements of the design. Kwak and kim (2008) determined section database to optimally design R\C plane frames. Zou and Chan (2005) performed an optimal resizing technique for dynamic drift design of R\C buildings under response spectrum and time history loadings. Kaveh and Zakian (2014) utilized a charged system search (CSS) algorithm as the meta-heuristic optimizer and optimally seismic designed R\C dual shear wall frame system and frame system. They created database for columns, beams, and wall members beforehand to be used as design variables. Some of the main provisions that have been used by them are from FEMA (2000, 2006) and ACI (2011).

The Nelder-Mead optimization algorithm is a widely used approach for non-differentiable objective functions and therefore, is most suited for machine learning and deep learning in design. As such, it is generally referred to as a pattern search algorithm and is used as a local or global search procedure. Originally the algorithm was for unconstrained optimization. In Python (OOP programming language) a "constrNMPy" package was written to handle constrained problems.

In this research an optimum design approach of shear-walled frames dual system consisting of three bays and five stories using constrNMPy package is executed. This dual system is an experimental specimen tested by Devi, G. N. (2013)[1].

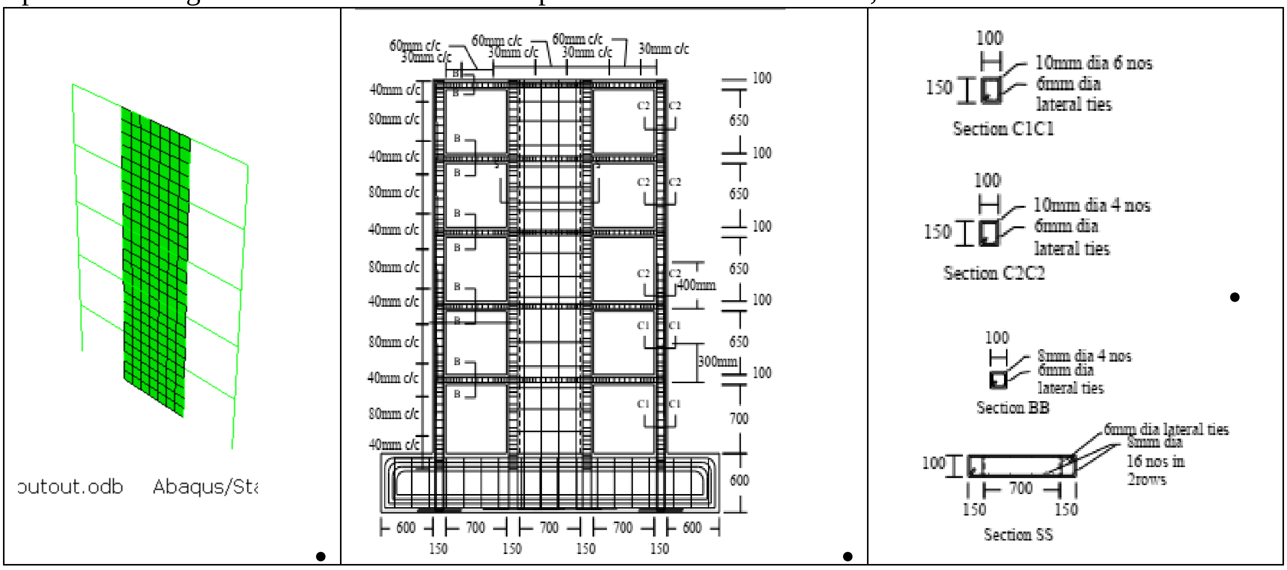


Figure (1) Left Abaqus numerical model, Center, Right specimen configuration Devi, G. N. (2013) [1]

behaviour. As for shear wall's material Abaqus's Concrete Damaged Plasticity is used, Hilleborg. A., M. Modeer, and P. E. Peterson (1976), Lee, J., and G. L. Fenves (1998)[3] , Lubliner, J., J. Oliver, S. Oller, and E. Onate (1989)[4].

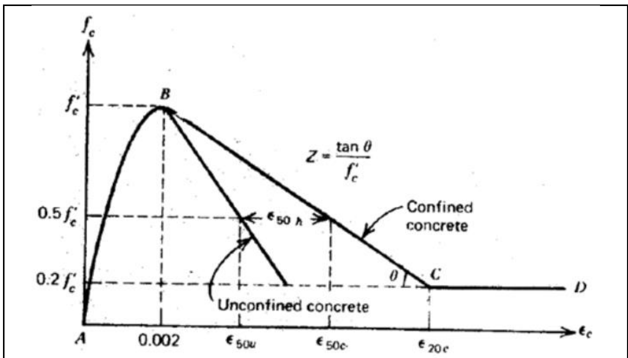
According to Vui V. Cao and Hamid R. Ronagh (2013)[5] the stress strain curve of concrete before reaching maximum stress is widely approximated as a second degree parabola, Hognestad, E. (1951)[6], Kent and Park (1971), Park and Paulay (1975)[7], Scott, B. D. (1980)[8]. While it continues as a negatively inclined line after that limit.

$$f_c = \acute{f_c}\left(\frac{2\varepsilon_c}{\varepsilon_0} - \left(\frac{\varepsilon_c}{\varepsilon_0}\right)^2\right) \quad for\ \varepsilon_c \le \varepsilon_0$$

$$f_c = \acute{f_c}\,\{1 - Z(\varepsilon_c - \varepsilon_0)\} \quad for\ \varepsilon_0 \le \varepsilon_c \le \varepsilon_{20c}$$

2- Modeling and Optimization Methods:

The model of analysis is created by nonlinear finite element package Abaqus ® [2] which comes with an implicit solver (Abaqus/standard). Abaqus's *.inp file is the text file format that has the numerical model written in certain syntax to be analyzed by Abaqus/Standard and, hereafter, creating different types of results with several output file formats. In the numerical model and for frame-like members such as columns and beams, beam element B31 is used. This element is 3-dimensional, linear function element that allows for transverse shear deformation (Timoshenko Beam). For Wall members, shell element S4R A 4-node quadrilateral, stress/displacement shell element with reduced integration. The materials' model for steel rebars and concrete beam elements is the elastic-perfectly plastic



Concrete Damaged Plasticity parameter	Symbol	Default Value	Selected Value
Dilation Angle in the p-q plane	ψ	-	35
Flow Potential Eccentricity	ϵ	0.1	0.1
Ratio of Initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress	σ_{b0}/σ_{c0}	1.16	1.12
Ratio of the second stress invariant on the tensile meridian q(TM) to that on the compressive meridian, q(CM)	K_C	2/3	2/3
Viscosity Parameter	μ	0	0.08
Stiffness compression recovery factor	ω_C	1	1
Stiffness Tension recovery factor	ω_T	0	0
Strain corresponding to $\acute{f_c}$	ε_0	0.002	0.0015
Inclination of $f_c - \varepsilon_c$ curve after $\acute{f_c}$	Z	100	100

Figure (2) Left- Model of concrete, Kent and Park (1971). Right- Used parameters of CDP material.

reinforced concrete dual structural system subjected to lateral load tested by Devi [1], was used as the reference experiment in this study. The force-deformation behavior of the model was compared with the results of the experimental results under the same loading conditions, after several trials a satisfactorily close result to the experiment is depicted on figure (3) Left.

In CDP model several parameters are given to control the behaviour of the concrete under compression, tension, and repetitive cycles of loading. The parameters shown on figure (2) are taken for the most successful trial in curve fitting analysis results to the experiment of Devi.[1]

In order to validate the results of modeling, an investigation of a quarter-sized three bay five story

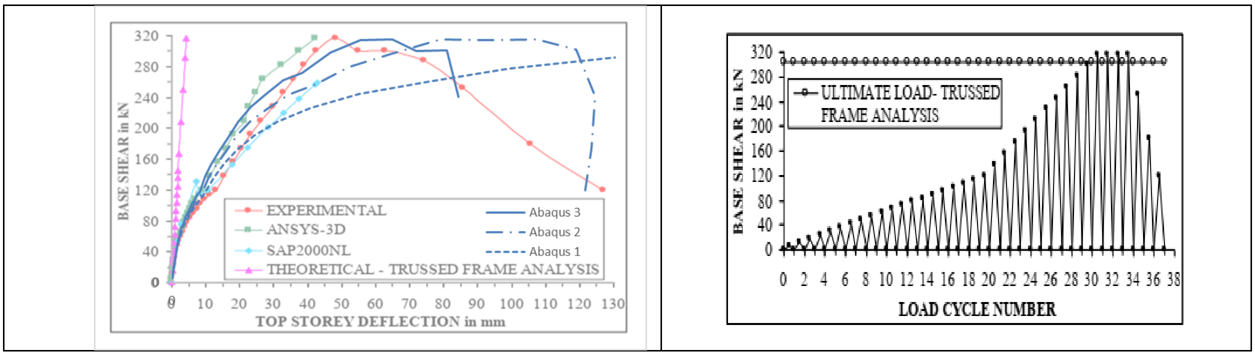


Figure (3) Left- Skeleton curves of experiment and Abaqus analysis, Right- Loading sequence

analysis finishes, the results are read from the output *.dat file. The data read are processed to compute design constraints. These constraints represent the code provisions and design limitations. Hence, a penalty value is calculated for every constraint violated and reflects the size of violation. The optimization algorithm is fed with the penalized objective function (cost of the structure plus summation of penalties).

In order to automate the modeling process of the dual system at every optimization cycle, a program on Python was written and thoroughly verified. This program calls the *.inp file that was created beforehand by Abaqus/CAE and fills the design variables with designated values (initial values are user suggested while optimizer should produce the next set of values at every cycle) then submits the *.inp file to analysis by Abaqus/Standard. After

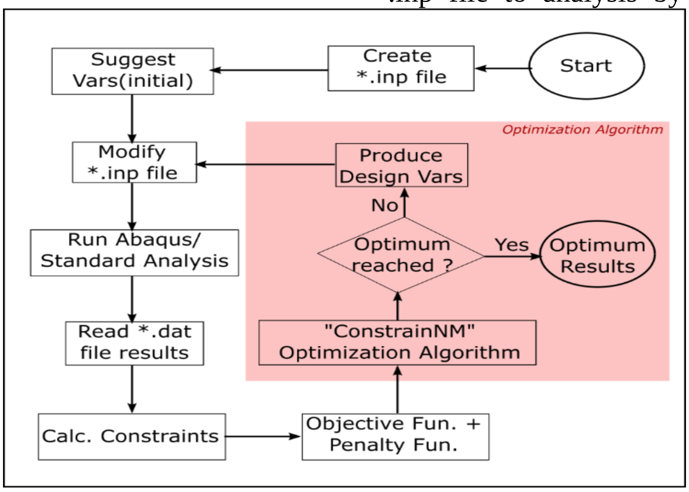


Figure (4) Optimized design process of a structural system using Abaqus

ratio (µ). In frame sections the variables are 3 (a, b, µ) and for walls they are 2 (aw, µ) because the length of wall section (bw) is architecturally fixed.

2.1 Design variables and Objective function:

The variables of the design are the dimensions of any cross section (a and b), plus the reinforcement

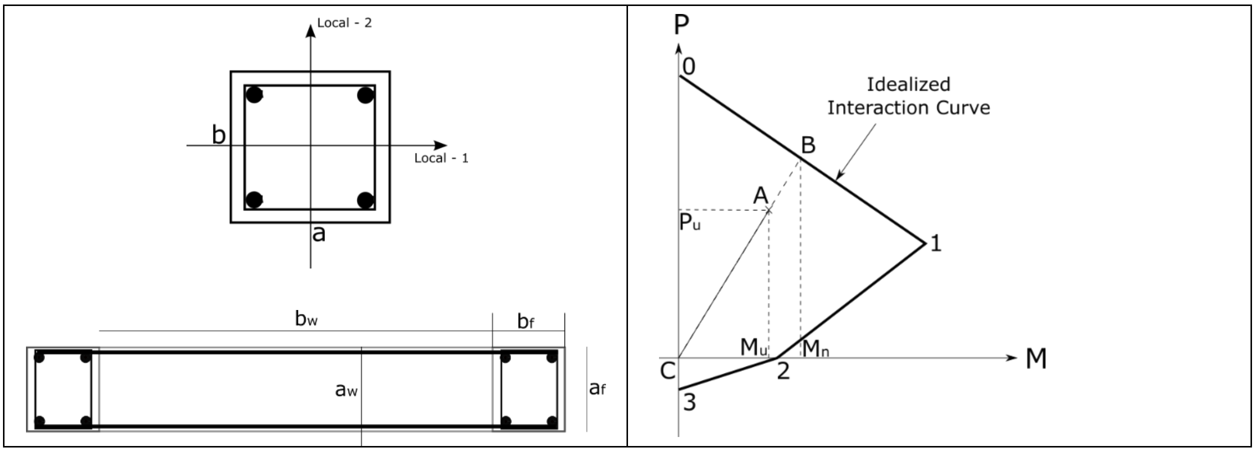


Figure (5) Left- Sections including design variables, Right- P-M interaction curve of a column

price of unit volume of concrete, unit weight of steel, and unit area of formwork (used in casting). Kaveh, A., & Zakian, P. (2014). [9].

On deciding the values of design variables either initially by the user or in every optimization cycle by the algorithm, the cost of all sections used in the model can be calculated with the reference to the

Table (1) formulas of sections' costs.

Member	Section's cost per unit length of member
Column	$\propto_1 \cdot A_S \cdot \gamma_S \cdot UCS + a \cdot b \cdot UCC + 2(a+b) \cdot UFC_{Column}$
Beam	$[2\alpha_2 \cdot A_S + (1-2\alpha_2) \cdot A_S] \cdot \gamma_S \cdot UCS + a \cdot b \cdot UCC + (a+2 \cdot b) \cdot UFC_{beam}$
Wall	$\alpha_3 \cdot A_{sw} \cdot \gamma_S \cdot UCS + a_w \cdot b_w \cdot UCC + [2 \times a_w + 2 \times b_w] \cdot UFC_{wall}$
$\propto_1, \propto_2, \propto_3$	Coefficients for development lengths of steel bars
γ_S , A_{Si}	Specific Weight of steel, cross sectional area of reinforcement
UCC , UCS	Price of unit volume of Concrete, price of unit weight of steel
UFC_{Column} , UFC_{Beam} , UFC_{Wall}	Price of unit area of column's, beams and wall's formwork respectively

2.2 Design Constraints:

12 design constraints are used in order to tune the design to meet the required provisions and standards of codes. 6 of these constraints are related to dimensions of sections and the relation between adjacent members' sections. These constraints need

Accordingly, cost-based objective function can be calculated for the whole model. In addition, half of all design constraints can be calculated based on this variables' values and before running the analysis of the model.

analysis if a certain criterion about penalty value is realized. The 7'th constraint (Cs7) represents the ratio of demand on capacity of a column section based on P-M interaction criteria (Figure (5)). If the length (AC) is less than (BC) while point A is on (BC) then the column section is marked safe. That means the constraint is fulfilled and the section's capacity is adequate. Table (2) contains the design constraints in summary.

not to have analysis results to be estimated. This is why they are called pre-analysis constraints. The remaining 6 constraints are related to the strength of the sections and the loading in members resulted from analysis. This is why those constraints are called post-analysis constraints. The idea behind making two groups of constraints is that pre-analysis constraints can be calculated once design variables are decided and hence, the analysis of this configuration can be cancelled to save the time of

Table (2) Design constraints considered in optimal design of dual frame

Cs	Type	Formula	Explanation	Reference
1	Pre-Analysis Constraints	a_{i+1}/a_i	Upward Consecutive columns have lesser equal a	ACI
2		b_{i+1}/b_i	Upward Consecutive columns have lesser equal b	ACI
3		A_{si+1}/A_{si}	Upward Consecutive columns have lesser equal As	ACI
4		$0.5A_{sb-TOP}/A_{sb-BOT}$	Positive-moment strength of beam section at the face of beam-column joint is greater than half the negative-moment strength	ACI
5		$1.2\ M_{nb}/M_{nc}$	Strong column weak beam	California Administrative code 2019 (4.3.6)
6		a_w/a_f	Boundary column's width is greater equal wall's width	ACI
7	Post-Analysis Constraints	L_{CA}/L_{CB}	The performance of a column lays within the P-M interaction curve	ACI (Fig. (5))
8		M_{ub}/M_{nb}	Maximum moment in beam section	ACI
9		P_{Wu}/P_{Wn}	Shear force in shear walls	ACI 318-14 (Table 11.5.4.6)
10		T_{Wu}/T_{Wn}	Tension force within boundary column	ACI
11		C_{Wu}/C_{Wn}	Compression force within boundary column	ACI
12		$maxDR/0.002$	Maximum drift ratio limit	ACI

$$P_i = \max([C_{S-i} - 1], 0) \times \beta_i \quad , \qquad Penalty\ Fun. = \sum P_i$$

Here β_i represents a weight factor to emphasize the penalty function of constraint i. In this research all weight factors are assumed to be 1000.

3- Optimal Design of Dual System:

It is notable that the code's provision on the frame part of a dual-system that must resist at least 25% of the lateral seismic loads according to FEMA-451 (2006) is not mentioned. This is due to the purpose of this research on finding this ratio after optimally designing the dual-system building.

After "computing" every constraint C_(S-i) for all respective members, the next formulas are applied:

and this will be phase-2 optimization. Two analysis types were considered. The first is a static analysis under pushover forces that equals to the ultimate capacity forces that were recorded in Devi's experiment. And the second is a dynamic nonlinear time history analysis under 1995 Kobe's earthquake (magnitude 7.2 on the Richter scale). For this purpose, a story loads of 14 Ton (mass) were assumed for every story because in the original experimental work no vertical loading on the tested structure is mentioned. After the optimization in both static and dynamic analysis terminated, the configurations of the resulted structures were remarkably different. For the static analysis the optimized design of the structure yielded huge sections with high-cost objective function. This is probably due to the high loading the structure was subjected to in the experiment till failure. In most cases this loading condition doesn't reflect a real type of loading or loading combination that is expected to affect the structure in reality. Rather, this type of loading is used to explore the capacity of the structure till failure. On the other hand, dynamic loading didn't cause the optimized design to suffer from excessive loading or deformations, therefore the resulted sections were relatively small and total cost was modest. This is due to loading condition that was the result of relatively small masses on every story (14 tons), and to some extent due to the changing response of the structure resulted from changes in configuration of sections while optimization process is taking place. The next table shows the optimized resulted:

In optimal design of a structure, the variables that cover designed aspects are considerably large in number so that they cover most of the design. This issue is critical in optimization for when using a large number of variables, the optimization algorithm will require large number of iterations and the final result may fall in a local minimum when optimization algorithm terminates. Therefore, decreasing the number of variables as much as possible will help the algorithm in working more efficiently and yields global results much faster. In this research's optimum design, the same sections' locations originally selected by Devi, G. N. (2013) [1] are also selected here to be the variables of design. C1 for columns' section of first and second stories, C2 for the third, fourth, and fifth. B for the section of all beams (Figure (1)). C3 for the section of shear wall's boundary elements, and W for the section of shear wall itself. A total of 3 ×4+2 ×1=14 variables are considered as design variables. In order to have better performance for the optimization algorithm, the 14 variables were reduced to 5 variables only by fixing the parameters of every section of C1, C2, C3, B, and W. Only one optimized quantity is considered for optimization within every section, the rest of the section's parameters are only related to this value by a fixed relation (e.g., a is optimized and b=a). This is called phase 1 optimization. After converging to an optimum, the fixation between the parameters of the same section is released, for this purpose the resulted optimized values from phase-1 are used as initial values for the 14 new variables

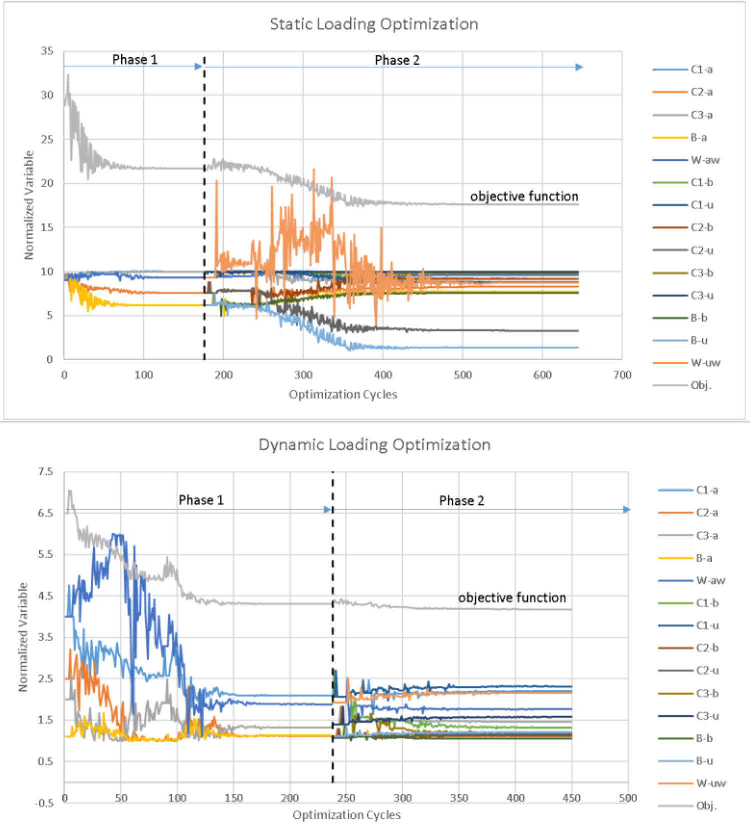
Table (3) Results of optimization on seismic design of experiment's specimen. Devi, G. N. (2013) [1]

Parameters of section	C1 [mm, mm, Ratio]			C2 [mm, mm, Ratio]			C3 [mm, mm, Ratio]			B [mm, mm, Ratio]			w [mm, Ratio]		Obj. [price]
	a	b	μ	a	b	μ	a	b	μ	a	b	μ	a	μ	
Static Ana.	498	459.8	0.0657	413.2	457.2	0.0247	441.2	490.5	0.0748	386.9	377.6	0.0105	480.1	0.0044	3525.7
Dynamic Ana.	110	66.1	0.0174	56.1	56.28	0.0087	73.2	60.22	0.0118	57.8	53.0	0.0091	88.2	0.0011	266.9

ing to the first selection of them in phase-1 optimization. For phase-2 optimization which involves all the considered design variables of the sections (including the parameters that were fixed in phase-1) the program begins another optimization process

From the behavior of design variables, it is obvious that the type of loading has a significant influence over their optimized values. In addition, when phase-1 terminates with certain values of the variables these values are considered optimized accordchanges of one or more parameters. While under static loading the response would change in less violent manner when sections' parameters slightly change. In many cases sight changes in some parameters might not result in any significant change in the response of the structure. Another interesting notice from the figure is that after phase-1 terminates and when initiating phase-2 taking the optimum variables' values of phase-1, the variance of design variables at the beginning of this phase was notable in the static analysis exclusively.

that would additionally refine the values of the 5 variables considered earlier and searches for more optimized values for all of the variables as a whole. For instance, in optimization phase-1 (5 variables) the convergence to near optimized values didn't occur before considerable number of cycles recorded. Namely 100 cycles for static and 150 cycles for dynamic. The cause of this difference is from the changing response with the alteration of structure's sections' parameters. Under dynamic loading the response might suffer abrupt changes from slight



Figure(6) Behavior of variables' changing during optimization.

strength in the static-loading optimized structure, which agrees with the provisions of codes that doesn't allow smaller than 25% for this participation ratio FEMA-451 (2006) [10]. This ratio dropped significantly to 1.01% for the dynamic-loading optimized structure, which is very small compared to the design shear strength of the shear wall in bearing lateral seismic forces.

After optimization in phase-2 terminated for both static and dynamic analysis, the frame part's strength for lateral shear forces ratio must be checked. First a capacity analysis under pushover loading for the dual-system was applied till failure, then the same analysis was performed for the structure with shear-wall not included in the model. This procedure is done for both static-loading and dynamic-loading optimized structures. The results were 62.5% participation of the frame part's design

In low and small structures (such as the one considered in this research) a dual system might not be the most suitable system for seismic resistance, therefore the results of optimization differed significantly between types of analysis. This ignites the need to optimally design more realistic 3D models of buildings.

• Optimization process can be more cost-effective if split into two or more phases while increasing the number of design variables from phase to phase.

4- Conclusions and Recommendations:

The resulted high ratio (62.5%) of frame part participation in the lateral design strength of the dual system under static loading optimization reflected heavy demand for the frame part. In contrast, the resulted ratio for the dual system under dynamic loading was significantly lower (1.01%) which indicates the importance of the type of loading and analysis considered in optimization.

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