Design of Experiments for Structural Model Updating of Steel Structure using Dynamic Testing

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Abstract: There can be a lot of uncertainty in material properties and dimensions of a structure when it comes to fabrication.For this reason, in many cases, the outcomes of the numerical and experimental modal analyses mismatch. For this, the numerical models of the structures need to be updated to match the experimental test results. Model updating is one way to develop a numerical model of structure in any analysis software by considering the dynamic properties.It is basically a method to equalize the dynamic properties of an existing structure with the structure being tested. The present study deals with the structural model updating of a three-storied steel building frame model using SAP 2000 and STAAD Pro V8i in comparison with the experimental results. The natural frequencies of the test structure are obtained using shake table testing or an impulse hammer test. The numerical model natural frequencies are simulated to match the experimental natural frequency (target value) using the proposed model updating technique. In this method, the material properties, geometrical element properties, damping properties of the structure are varied within the desirable upper and lower limits. Design of experiment (DOE) is adopted to predict the suitable chosen parameters to be varied by introducing valid upper and lower limits to the input (dependent) variables, output (response) variables, and control (constant) variables. The numerical results obtained from SAP 2000 and STAAD Pro V8i are then compared with the experimental results by varying different material and geometrical elemental properties thereby suggesting successful implementation of DOE. It is also observed that the model designed in SAP 2000 results are closely matching with experimental results and is considered to be accurate compared to STAAD Pro. Also, the comparison of earthquake response for experimental structure and numerical model are carried out and the responses are very well matching.

Index Terms: model updating, natural frequency, SAP 2000, STAAD pro.

I. INTRODUCTION

Requirements of the designs usually rise from various economic and environmental aspects which also be controlledby governing forms for safety standards and performance-related issues of machinery.Computer-based analysis techniques have changed the design and development ever since in many other industries to a large extent. In structural dynamics, traditional study of the structures connected to the modal properties of the system.Various numerical linking tools were upgraded for the authentication of the predicted and measured quantities and algorithms for the improvement of FE models using the measured dynamic properties which were involved with success.

Differentiating the direct approach and developing a mathematical model which is capable of duplicating a given state is the goal of finite element model that is to achieve an improved match between model and experimental data by doing physically meaningful changes to model parameters. Afinite elementmodelcan be used to model various loading conditions, boundary conditions, or configurations without experimental testing.

Model updating using finite element become a workable method to improve the correlation between the dynamic response of a structure and the estimates from a model. Here the parameters are so adjusted to decrease a penalty function which depends on residuals between a measurement set and thepredictions of the model. Quintessential measurements usually including the natural frequencies and mode shapes and the frequency response functions. Efficiency of modal-based model updating techniques dependent on the quality of the modal parameter. So for that, doing analysis on the measured FRFs for the identification of the modal parameters of system is a process that introduces inaccuracies which already present in the measurements. Model updating is mainly skilled by a “trial-and-error” approach. Model updating becomes more tough for now and systematic approaches are necessary to solve problems.

Different dynamic responses considered for model updating:

Centre of gravity and mass moments of inertia.

- Static displacements
- Strain
- Resonance frequencies
- Individual modal displacements
- MAC-values
- Frequency Response Functions (FRF) values
- FRF Correlation Functions values
- Displacement, velocities or accelerations

Different structural parameters considered for model updating are:

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- **Properties of material** - Young's modulus, poisson's ratio, shear modulus and mass density.
- **Geometrical Properties** - Spring stiffness along with plate thickness and beam cross-sectional properties.
- **Lumped properties** - Lumped stiffness and lumped masses.
- **Damping Values** - Modal damping, Rayleigh damping coefficients, viscous and structural damper values too.

Parameter can be selected at the local or global level:

- **Local parameters** indicates an individual element and **Global parameters** indicates sets of elements selected instead of an individual element.

Differences between FEA and test data arise due to uncertainty in the governing physical relations that is modelling non-linear behaviour with the linear FEM theory. The effects on the Finite Element Analysis results requires analysis and improvements must usually be made to reduce the errors associated with the FE model. Approval of model updating for using measured structural data to correct the errors in Finite Element models has become extensively accepted.

II. ADVANTAGES

When design stage is considered, the shaking behaviour of a future structurecan be projected by a Finite Element modelby modifyingthe design of that structure which should found before the construction of structure. After the construction of the structure, modal and other tests can be done for validation of the FINNITE ELEMENT model. Once the model is ready to predict the measured behaviour with a tolerable lower limit of accuracy, then further analysis like response prediction, structural coupling, stress analysis, life time prediction, etc can be checked.As there are different limitations and assumptions implied in the two approaches, the FE model and experimental modal model have dissimilar characteristics and different advantages and drawbacks. The Finite element model generally possess a large number of coordinates by which the vibration characteristics can be defined in detail. In contrast, the experimental data and modal properties are generally measured to be least close to the true representation of the structure, because modal testing is done with the actual structure rather than an idealised structure. The information which we obtain is available primarily as selected modal parameters, rather than the full spatial properties provided by the FE model. The criteriaof correlating the models derived from these two different approaches is to make correlate the advantages of both and to overcome the disadvantages for the best. Experimental modal data proves is more accurate than the FE model. Hence, development of model updating schemes which aim is to improve or to correct the initial FE model using modal test results has happened.

III. OBJECTIVE OF THE STUDY

The design of an updating model that can generate an advanced analytical model which can not only generate the accurate modal parameters measured in a dynamic testing also can capable to predict the modes outside frequency range of the experimental data and also decreases computational time for updating. Accuracy occurred in the updating results and not only in modal parameters but also in correction coefficients and it can handle all the inherent incompatibilities between measured modes and the analytical model properly.

IV. LITERATURE REVIEW

Friswell M and Mottershead J E **(1995)** mentioned the drawback of upgrading a numerical model by taking into consideration of data collected from a substantial vibration test and concluded that the most popular approach for numerical modelingis the basic finite element method.

M.Aghagholizadeh and F.N. Catbas**(2015)** used Bayesian model updating and error domain model falsification methods investigating features and disadvantages of deterministic and probabilistic approach.

Jie Wu, Quansheng Yan, Shiping Huang, Chao Zou,Jin tu Zhong,and Weifeng Wang**(2018)**developed and studied Kriging model and Latin hypercube sampling method, for finite element (FE) model upgrading and verified the algorithm for a truss bridge and an arch bridge. ***Ming Zhan, Qintao Guo and Lin Yue, (*****2018)** didmodel updating of a typical bolt-jointed structure by carrying outmodal tests and experimental modal analysis of substructures and built-up structure by using hierarchical model updating strategy based on Bayesian inference. ***Martin Jull and SandroD.R. Amador, (*****2018)**described the importance of matrix mixing model updating technique combined with the local correspondence (LC) mode shape expansion algorithm, to generate a new finite element (FE) model updating method by whichFE models can be updated in one-step with less errors. ***Mohammad I.Younis,*** **(2014)** suggested to construct a transformation matrix and use it to rectify the analytical eigenvectors by which the updated model can be similar with the measurement of the eigenvectors, thus preserving the symmetric positive definiteness of the mass and stiffness matrices. ***Danhui Dan, Tong Yangandand Jiongxin Gong,*** **(2013)**used the software systems ANSYS and MATLAB to accompany different bridge types and different model updating needs.

V. METHODOLOGY

Analysing dynamically mainly focuses to grasp, assessing, analysing and changing (if necessary) the structural behaviour dynamically. Robust behaviour of the structure can be depicted in terms of natural frequencies, eigenvalues, mode-shapes, damping ratios, frequency response functions etc. Again, analysing the dynamic behaviour of structures, experimental method or conceptual approach can be adopted whichever is feasible and important. Theoretical path usually demands the analytical model to be formed of the system either using a traditional method or through finite element (FE) method. Applying traditional method is usually limited to simple systems only, while FE method is demanded for real life complex systems. Moreover, dynamic responses of structures with perfect accuracy can't be predicted by using finite element model because of the presence of certain errors such as wrong values of material (like modulus of elasticity, density etc.) and structural (like thickness, moment of inertia, etc.) properties. Thus the need to update an FE model arose so that its vibration behaviour corresponds with experimental dynamic response. This metho of updating the FE model is named as finite element model updating (FEMU). At present,FEMU has been assumed as a multi objective optimization problem. In such type of problems, experimental responses are regarded as targets, while parameters of FE model are identified, corrected and updated in such a way to match the FE responses with corresponding experimental response values. Therefore, present research work aims at presenting a more detailed, flexible, simplified, and user-friendly formulation of objective functions of FEMU. Setting the target value from experimental response, desired higher and bottom limits on predicted frequency, weights on higher and bottom limits, and, comparative importance for each sub-objective separately. Thus this model updating procedure can be summarized into following steps:

- The method is started by choosing the domain in which data is presented first. The domains used incorporate time domain, frequency domain, modal domain, time-frequency domain and other dynamic properties.
- Second part the determination of which parts of the initial models are thought to have been incorrectly designed, i.e. identifying and locating errors.
- The third task is to select suitable parameters to be varied by introducing valid upper and lower limits to the input (dependent) variables for getting desired output (response) variables by choosing proper control (constant) variables.
- The fourth step is to carry out number of trails in FE modelling by varying the input variables that would bring about change in output variables (response) such that we end up with exact experimental results.

VI. DETERMINATION OF FINITE ELEMENT AND SIMULATED NATURAL FREQUENCIES FROM EXPERIMENT

SAP 2000 and STAAD.Pro were used to design the finite element model of the 3D frame by using multiple beam and column elements each having prescribed number of nodes. First 12 modes were developed in the finite element model. After that check was done for the model by decreasing the elastic modulus and increasing material density proportionally. The so called FE model that was not updated undergonemultiple times with different values of density and young's modulus within specific limits to produce the simulated experimental results.It is clearly visible that initially there exists a difference between FE and experimental results.Main aim of the FEMU was to lower the above mismatch by updating the various geometric and material properties of FE model.Theresults obtained experimentally were considered as basis for choosing the specifications for updating for the above reason; simultaneously updating other parameters by using the newly developed optimization techniques. Experimentally obtainedvalues are then compared which were again used in conjunction with FE model of beam that is not updated to determine the corresponding structure'snatural frequencies.

VII. PROCEDURE

Selecting a 3D frame model

↓

Identifying and measuring parameters

↓

Calculating experimental frequencies

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Designing in SAP 2000 and STAAD Pro

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Comparison between FE and experimental frequencies

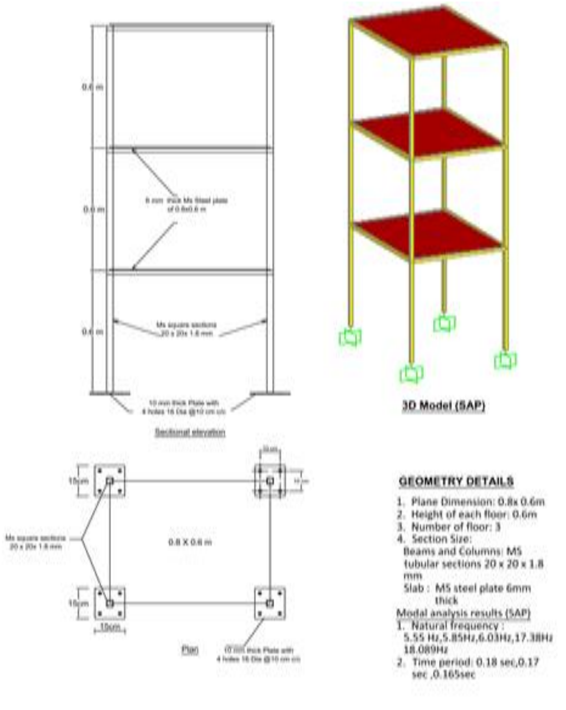
↓

Updating the FE model

↓

Conclusion and future scope

A. Model selected for updating



B. Measuring the dimensions of 3d frame

The dimensions of the selected 3D frame are measured using Vernier callipers and screw gauge. Dimensions of each member like column, beam and slab at different locations and average value is adopted. The error in the

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dimension can be obtained by comparing the measured dimension with design dimensions. The measured dimensions of the frame along with the variations are tabulated below.

C. Beam and column thickness at each floor

Ground floor:

Beam no	End thickness (mm)	Middle thickness (mm)	End thickness (mm)	Average
B11	19.42	19.30	19.37	19.3633
B12	19.34	19.35	19.30	19.33
B13	19.27	19.25	19.30	19.27
B14	19.40	19.45	19.40	19.416

Average of all beam thickness at ground floor =19.343mm
Variation of beam thickness at ground floor = 20-19.343 =0.657mm.

First floor:

Beam no	End thickness (mm)	Middle thickness (mm)	End thickness (mm)	Average
B21	19.40	19.42	19.45	19.42
B22	19.37	19.32	19.38	19.35
B23	19.21	19.21	19.29	19.23
B24	19.31	19.25	19.31	19.29

Average of all beam thickness at ground floor = 19.32mm
Variation of beam thickness at ground floor = 20-19.322=0.678mm.

Second floor:

Beam no	End thickness (mm)	Middle thickness (mm)	End thickness (mm)	Average
B31	19.28	19.21	19.22	19.23
B32	19.43	19.44	19.46	19.44
B33	19.49	19.40	19.38	19.423
B34	19.23	19.34	19.34	19.303

Average of all beam thickness at ground floor = 19.349 mm
Variation of beam thickness at ground floor = 20-19.349 = 0.651 mm.

Average of all beam thicknesses at each level = (19.343+19.322+19.349)/3 =19.338mm.
Average of all variations = 0.662mm.

Range considered for updating (beam and column thickness) = (-0.5mm to +0.1mm).

D. Tubular column height

Ground floor:

Column no	Height (mm) c/c
C1	599
C2	604
C3	595
C4	593

Average = 597.5 mm.

First floor:

Column no	Height (mm) c/c
C5	600
C6	600
C7	600
C8	603

Average = 600.75 mm.

Second floor:

Column no	Height (mm) c/c
C9	597
C10	600
C11	601
C12	600

Average = 599.5mm.

Average of all column heights for each floor = 599.25mm
Variation = 600-599.25=0.75.
Variation considered for updating = (-1mm to 0.25mm).

E. Slab thickness

Plate no	End thickness (mm)	Middle thickness (mm)	End thickness (mm)
P14	6.184	6.174	6.153
P13	6.191	6.156	6.167

Ground floor average plate thickness = 6.17 mm

Plate no	End thickness	Middle thickness(mm)	End thickness (mm)
P23	6.123	6.174	6.173
P24	6.12	6.162	6.221

First floor average plate thickness = 6.1615 mm

Plate no	End thickness	Middle thickness (mm)	End thickness (mm)
P33	6.177	6.185	6.183
P34	6.165	6.135	6.14

Second floor average plate thickness= 6.163 mm
Variation considered for updating = (-0.05mm to 0.2mm)

F. Beam length (inner to inner): plan- 0.6mx0.8m

Beam no	**Length (mm)**
B11	580
B21	580
B31	580

Average = 599.406 mm.

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Beam no	Length (mm)
B12	777
B22	780
B32	780

Average = 779 mm

Beam no	Length (mm)
B13	580
B23	582
B33	577

Average=599.076 mm

Beam no	Length (mm)
B14	780
B24	782
B34	777

Average = 799.67 mm

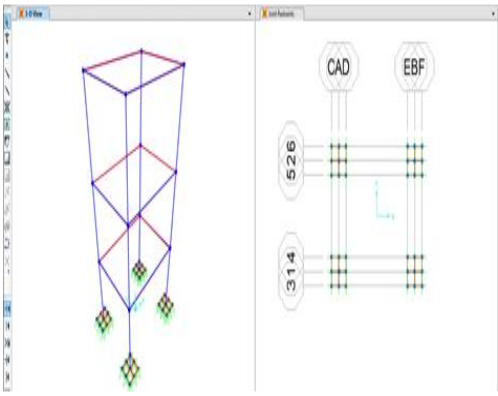
Variation considered in 600mm side = (-1mm to 0.25mm).

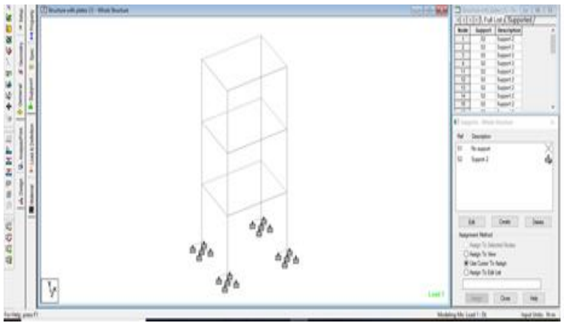
Variation considered in 800mm side = (-2.5mm to 0.25mm).

Range of the parameters to be updated**:**

S.No	Parameters	Variation
1.	Young's modulus	190GPa-210GPa
2.	Density (rho)	7800-7900(kg/m^3)
3.	Dimensions	<u>Beam length</u> 797.5-500.25(mm) 599-600.25(mm) <u>Beam thickness</u> 19.5-20.1(mm) <u>Column height</u> 597.5-600.1(mm) <u>Column thickness</u> 19.5-20.1(mm) <u>Plate thickness</u> 5.95-6.2(mm)

G. Designing the frame model in SAP and STAAD





H. Comparison of SAP and STAAD results with experimental results

(SAP RESULTS)

	MODE	FREQUECNY	ERROR (%)
Trail-1	0.6mX0.8m, E=200Gpa, DESNSITY = 7850kg/m^3		
	1	5.55081	0.923
	4	17.3859	3.295
	9	28.93715	2.78
Trail-2	0.6mX0.8m, E=198Gpa, DESNSITY = 79000kg/m^3		
	1	5.55081	0.923
	4	17.3859	3.295
	9	28.93715	2.78
Trail-3	0.6mX0.8m, E=198Gpa, DESNSITY = 79000kg/m^3		
	1	5.5042	0.07
	4	17.23993	2.47
	9	28.7299	1.88
Trail-4	0.6025mX0.8025m, E=191Gpa, DESNSITY = 7830kg/m^3		
	1	5.44277	-1.0514
	4	17.00066	1.1038
	9	28.22826	0.1428
Trail-5	0.6025mX0.8025m, E=193Gpa, DESNSITY = 7820kg/m^3		
	1	5.47376	-0.48
	4	17.09744	1.66
	9	28.38896	0.704

(STAAD results)

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	MODE	FREQUECNY	ERROR (%)
Trial-1	0.6mX0.8m, E=200Gpa, DESNSITY = 7850kg/m^3		
	1	5.797	5.123
	4	17.854	5.830
	9	29.171	3.390
Trail-2	0.6mX0.8m, E=190Gpa, DESNSITY = 7900kg/m^3		
	1	5.645	2.568
	4	17.372	3.217
	9	28.358	0.599

(EXPERIMENTAL RESULTS)

S. No	**Experimental Frequency (Hertz)**
1	5.5
2	16.813
3	28.188

VIII. CONCLUSIONS AND DISCUSSIONS

Finally, the natural frequencies which were updated using Finite element model (mode 1, 4, 9 were chosen because the natural frequencies of 3D frame were calculated along the direction of shaking during experiments) are hence closely resembling the required experimental results; thereby proving the validation of the current FEMU technique. At last, the results that were experimentally calculated were estimated with the model designed in the software. It is evident that this present Finite element model updatingmethod has effectively controlled and lessen the mistakes in Finite element expected outcomes with great accuracy.

As per the user's requirements, the target values, bottom value, higher value, weight on lower value, weight on upper value and each response variable priority can be set by the above method. Above explained approach of finite element model updating is very beneficial in case of unlike quivering modes that are not important in the same base but have variousimportance and aspects. Validation of the proposed approach is done by the experimental claim on FEMU of a simulated frame anatomy. Parameters which are chosen should have physical meaning and also help in modelling and represent any mistakes present in the finite-element model. Configuration specifications, inclusive elements and identical models were provedbetter for updating the model. Applying limitations on the parameters, such as decreasing the gap between identical parameters, gives better results. Drawback seen in the above approach is predicting the comparative weight given to various limitations.

S.no	Parameter	Original	Updated
1	Staad pro Young's modulus Density	200Gpa 7850kg/m^3	190Gpa 7900kg/m^3
2	SAP Young's modulus Density	200Gpa 7850kg/m^3	193Gpa 7820kg/m^3

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