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A Smart Structures Concept for Truss and Tower Systems

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Abstract: Truss and tower are normally designed for specified loads. But in certain cases, they may be subjected to loads over the design values. The objective of this study, is to provide a smart control, which comes into effect only when the specified loads are exceeded by certain margins. To demonstrate the introduction of smartness, a three-dimensional, three-panel tower system is chosen. Actuators, which activate corrective control to externally applied forces at the nodes of the tower, are provided on the members of the tower. The control forces within an active control system are typically generated through actuators based on feedback information from the measured response of the structure. This study focuses on providing in-built smartness to handle both force and deformation when unanticipated loads up to 100% increase over a short duration act on these systems. The example highlights how suitable control forces are generated and how the system under combined action of unanticipated and control forces balanced.

Key words: Smart structure, adaptive structure, unanticipated loads, seismic loads, tower systems, sensors, actuators, active control

INTRODUCTION

Studies into active control of civil engineering studies have flourished since its introduction to the field by Yao (1972). An adaptive structure is defined as a structural system whose geometrical configuration and inherent structural characteristics such as damping, can be changed in order to adapt to environmental changes or to meet the mission requirements (Soong, 1990).

Power and communication virtually control the various activities of the society. The lines of power and communication become life line systems of the modern age. The hardware aspect of these life line systems namely steel towers, need to be properly designed so that failure is prevented under any circumstance. In the power and communication systems, the unanticipated loads are mostly in the forms of cyclone and earth quake. The design codes and material strengths are so formulated that probability of failure for unanticipated loads is kept within certain limits. Failures of transmission line towers and micro wave towers are quite common. At some point it may no longer be prudent to rely entirely on the strength of the structure and its ability to dissipate energy to withstand these extreme loads. Hence, instead of putting a premium on the design, it is preferable to look up for an alternative approach, through which a structure can withstand unanticipated loads without failure and return to its normal state under normal loads. This concept is called SMART or adaptive structural system. Active control strategies for structural systems have been developed as one means to minimize the effects of these environmental loads (Lee *et al*., 2000).

Features of adaptive structural systems: Normally structures are designed and constructed based on criteria stipulated in design codes and left unattended till their design life. In modern parlance, this is called passive design (Sivakumar *et al*., 1999) mainly because the system does not know its performance and is incapable of reacting to any unanticipated situations. Historically this has been the only design methodology available and practiced by structural engineers. With advances in sensor, actuator and microprocessor technologies, it has, now become feasible to monitor the performance of a system in terms of its deflections or stresses. Based on this information, it is feasible to actively control some of the responses of passively designed structure in real time to help in reacting to unusual situations. An adaptive structure is an engineering structure whose response to excitations can be sensed and if in excess, can be controlled in real time by either the insertion of internal deformations or inducement of force-type loading through appropriately placed actuators that are part of the structure.

When a structure at its reference state is subjected to a load, it assumes another state. The difference between

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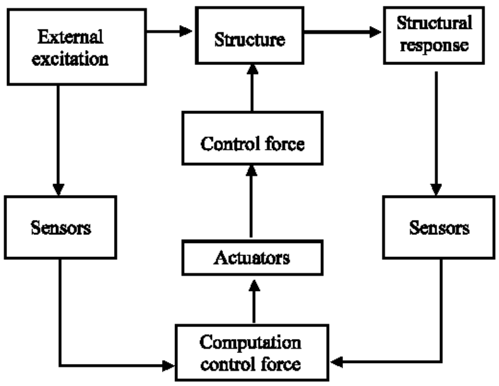

Fig. 1: Active control feedback loop

these two states is called the response of the structure (Senoul Utku, 1998). They are generally displacement, stress and strain. In adaptive structures, one or more response components are monitored, i.e., measured continuously. The devices that make the measurements are sensors. When the measures of monitored response quantities exceed, they are reduced by subjecting the structure to an additional set of excitations, which may minimally alter the existing stress or internal force. The device that creates and applies these differential excitations on the structure is actuator. The actuators are devices that compensate deviation from the nominal value in number of controlled response components. If these components become unacceptably large, they can be compensated by a control loading that would create opposing forces to the measured displacements.

If an actuator induces force-type loading at the nodes then it is called a force inducing actuator. The measurement of the disturbances and the computation of control to compensate them, may be depicted through a feedback loop as shown in Fig. 1 (Soong, 1990).

In this study, the control mechanism is illustrated through an example of a tower system. Tower is chosen because of the wide application in areas of power and communication. The focus of the study is to introduce smartness in such systems, so that the buckling can be overcome by external actuation eliminating lower buckling modes (Sato *et al.*, 1992) to ensure that the failure of the system does not take place even during critical times.

Tower system chosen for the study: To demonstrate the introduction of smartness, a 40 member tower as shown in Fig. 2 under lateral load is chosen. Grouping of the members into design groups namely leg members, horizontal bracing members and diagonal bracing members were done from the design point of view. The geometry and load details are given in Table 1-3.

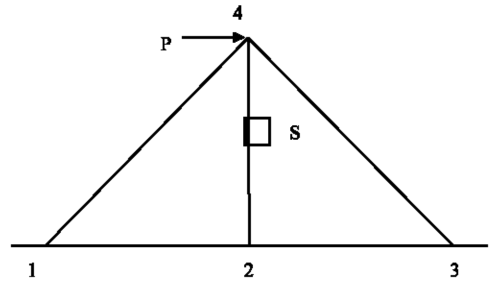

Fig. 2: Trust with actuator

Table 1: Structural details of tower

Description of members	Member chosen	Sectional area Sq.mm
Bottom panel leg members	ISA 80×80×8	1221
Middle panel leg members	ISA 70×70×8	1058
Top panel leg members	ISA 50×50×6	568
Bottom panel diagonal bracings	ISA 40×40×6	447
Middle panel diagonal bracings	ISA 45×45×6	507
Top panel diagonal bracings	ISA 50×50×6	568
Top panel beam members	ISA 45×45×6	507

Table 2: Details of design load

		Design load in N		
Sl. No.	Node	Fx	Fy	Fz
1	4	40000	0.00	0.00
2	12	40000	0.00	0.00

Table 3: Nodal coordinates

Node No.	X coordinate (mm)	Y coordinate (mm)	Z coordinate (mm)
1	0.00	0.0	0.00
2	166.67	2500.0	166.67
3	333.33	5000.0	333.33
4	500.00	7500.0	500.00
5	2500.0	7500.0	500.00
6	2666.6	5000.0	333.33
7	2833.3	2500.0	166.67
8	3000.0	0.0	0.00
9	0.00	0.0	3000.00
10	166.67	2500.0	2833.30
11	333.33	5000.0	2666.60
12	500.00	7500.0	2500.00
13	2500.00	7500.0	2500.00
14	2666.60	5000.0	2666.60
15	2833.30	2500.0	2833.30
16	3000.00	0.0	3000.00

MATERIALS AND METHODS

Unanticipated loads: Loads on structural systems are normally classified into service or working loads and ultimate or extreme loads and these are very well enunciated in various codes of practice. Once the design is done, the philosophy is that the structure will perform within the limits prescribed both in material and function. But a different scenario presents itself if the design loads are exceeded albeit for a short while. It is not worthwhile redesigning the structure for such situations. Instead if the system is allowed to have a mechanism by which it can sense, be aware and take action to counter this extra load the system is saved with marginal extra cost. In this study, these scenarios are demonstrated by increasing the design load in four stages and discussing alternate ways of making the structure adaptive or smart as per the previous definition.

Stage I : 25% increase in design load
Stage II : 50% increase in design load
Stage III: 75% increase in design load
Stage IV: 100% increase in design load

Method of introducing smartness: In this method the actuators can insert deformation into tower elements. They are called deformation-inserting actuators. A simple example of deformation inserting actuator is a turnbuckle embedded in a truss as a truss bar as in Fig. 2, a statically indeterminate truss subjected to load at node 4. Without the turnbuckle, the member 1-4 is subjected to tension while the member 3-4 is subjected to compression.

A deformation inserting actuator S is fixed in the member 2-4 to control the stress in the compression member. When the load P increases, the compression member 3-4 reaches the stress beyond the allowable stress value. To prevent the increase in stress beyond the allowable value, the actuator may be set to introduce deformation Δ into the member 2-4 such that a force equal to $AE\Delta/L$ acts at node-4, altering the stresses in all the members and doing so bringing back the stress in the compression member to within safe limit. This principle is used in the tower to withstand load in excess of the design load. However, it should be noted that the above process, while reducing the compressive stress in the member 3-4 to safe limit, may increase the tensile stresses in other members beyond their design strength. Thus the control algorithm shall be so designed to overcome such an eventuality.

There are fourteen members identified in the tower to fix the actuators, six diagonal bracing members, six leg members and two horizontal bracing members. Unit deformations are introduced in each of these actuators in isolation and the unloaded tower is analysed to determine the force distribution in all the members due to the nodal force induced by the deformation. This analysis is then iterated by combining the effect of simultaneously actuating deformation in more than one actuator to obtain the maximum effect in the balancing member forces. With this information, for every stage of increase in loading, the choice of actuators is determined and deformations are induced through the actuators to create balancing member forces to bring back the member forces to within design limits. This procedure is repeated for each step of load above the design load and the results are studied.

RESULTS AND DISCUSSION

Stage I: 25% increase in design load: An increase in the load by 25% more than the design value, produces forces higher than the design ones in twelve members six column members, two horizontal bracing members and four diagonal bracing members. All these members are compression members. To counter these excess forces, ten members are identified in the tower to fix the actuators-four in the leg members, four in the diagonal bracing members and two in the horizontal bracing members by the procedure earlier described and actuated. The increase in the member forces due to overload condition and the forces after getting balanced are illustrated in Fig. 3. The actuated members are 8-7, 16-15, 7-6, 15-14, 4-6, 14-12, 8-2, 16-10, 4-5 and 12-13.

Stage II : 50% increase in design load: An increase in the load by 50% more than the design value, produces forces higher than the design ones in fourteen members-six column members, two horizontal bracing members and six diagonal bracing members. To counter these excess forces, ten members selected as for stage-I Fig. 4 shows the increase in the member forces due to overload condition and the forces after getting balanced.

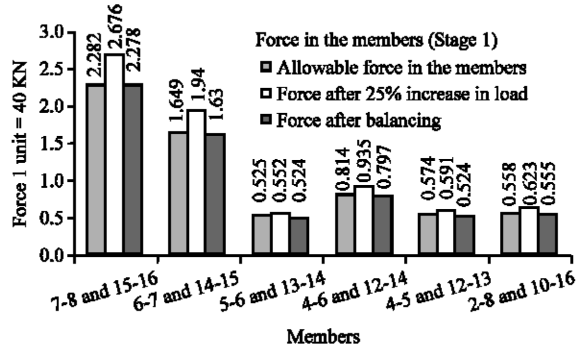

Fig. 3: Force in the critical members (Stage I)

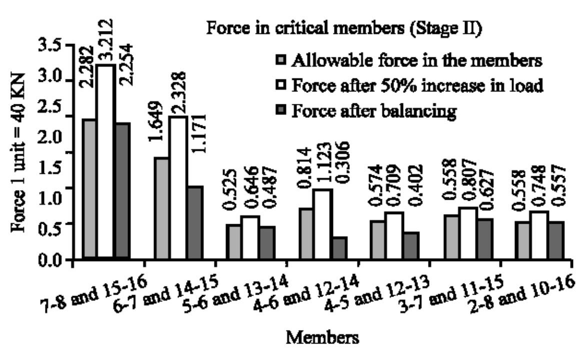

Fig. 4: Force in the critical members (Stage II)

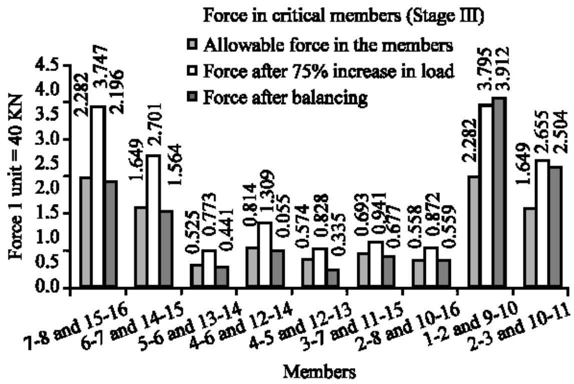

Fig. 5: Force in the critical members (Stage III)

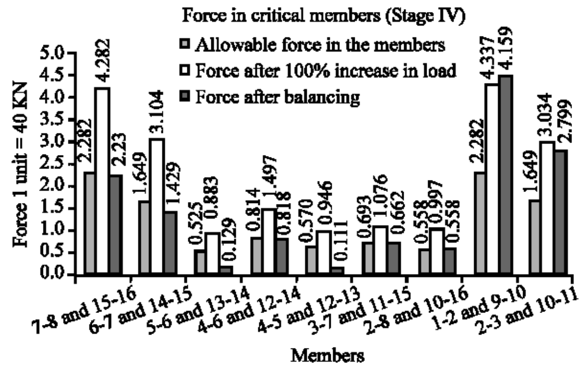

Fig. 6: Force in the critical members (Stage IV)

Stage III: 75% increase in design load: An increase in the load by 75% more than the design value, produces forces higher than the design ones in eighteen members-ten column members, two horizontal bracing members and six diagonal bracing members. To counter these excess forces, in the eighteen members in the tower ten members selected to fix the actuators, as for stage-II. Figure 5 shows the increase in the member forces due to overload condition and the forces after getting balanced.

Stage IV : 100% increase in design load: An increase in the load by 75% more than the design value, produces forces higher than the design ones in eighteen members-ten column members, two horizontal bracing members and six diagonal bracing members. To counter these excess forces, in the eighteen members, twelve members are selected to fix the actuators-four in the leg members, four in the diagonal bracing members and two in the horizontal bracing members-are identified by the procedure earlier described and actuated. The actuated members are 8-7, 16-15, 7-6, 15-14, 4-6, 14-12, 8-2, 16-10, 4-5, 12-13, 6-5 and 14-13. The increase in the member forces due to overload condition and the forces after getting balanced are illustrated in Fig. 6.

It can be clearly seen from these figures that the forces produced by the deformation induced by the actuators are able to successfully balance the excess forces in the compression members due to increase in loading on the structures beyond the design capacity. Figure 7 depicts the compressive force in the leg members at various stages of loading before and after balancing.

However, it is interesting to find out what is happening to tension members while the excess forces are getting balanced in compression members due to the deformation inducing actuators at various stages of overload. Figure 8 depicts the tensile force in the leg members at various stages of loading before and after

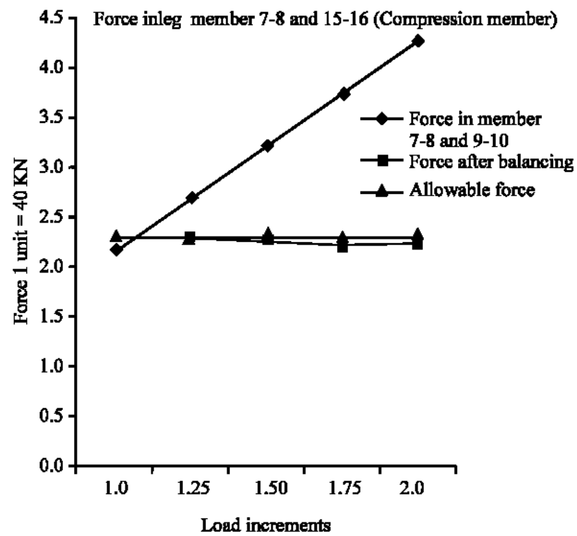

Fig. 7: Force in compression leg members 7-8 and15-16

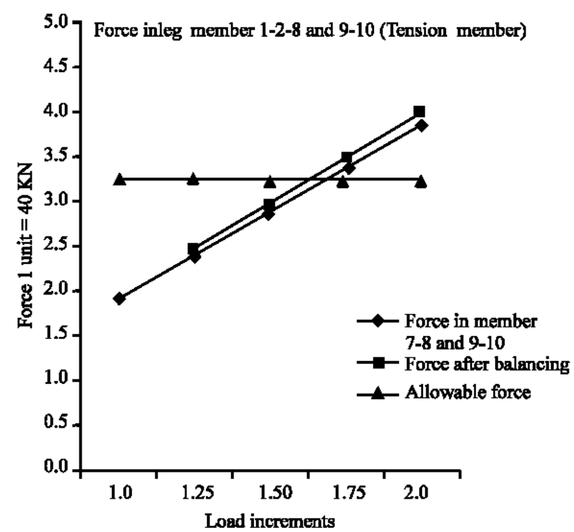

Fig. 8: Force in tension leg members 1-2 and 9-10

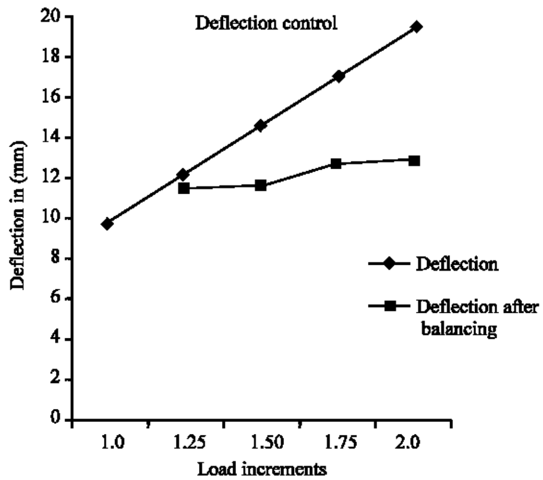

Fig. 9: Maximum deflection

balancing. From this figure, it can be seen that beyond 62.5% overload the tensile force in the leg members overshoots the allowable limits, indicating that these members yield while compression members are still safe. This puts a constraint on how for the smartness or the adaptability of the structure be harnessed through active control without redesign. In fact the elastic analysis performed beyond this stage becomes invalid.

Figure 9 shows the maximum deflection of the tower at various stages of over load before and after control. It clearly indicates the effectiveness of the control for reduction in deflection.

CONCLUSION

From the analysis and results of the study, it can be concluded that

- The reduction in compressive strength due to buckling can be overcome by external actuation eliminating lower buckling modes.
- Certain smartness are adaptive character can be built into a structure through introduction sensors, actuators and control algorithms as a part of the structural system, such that the structure can resist to a certain extent unanticipated overload.
- The example presented in the study brings out the efficacy of such concepts.
- The smartness that can be in-built into the system has certain limitations.
- The smartness can effectively reduce the maximum deflection of the structure.

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