Active Control of Buckling using Piezo-Ceramic Actuators

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Abstract

The buckling of compressively-loaded members is one of the most important factors limiting the overall strength and stability of many structures. This paper presents experimental results showing that active control can be used to stabilize compressive members against buckling, allowing them to be loaded well in excess of their critical buckling load. Experiments conducted using a composite steel/piezo-ceramic column achieved a factor of 5.6 increase in load-bearing capability through active stabilization of the first two uniaxial buckling modes. In addition, a small-scale railroad-style truss bridge was constructed to demonstrate that multiple actively stabilized compressive members may be incorporated into a compound structure. This paper presents an overview of the experimental results, suggests design criteria for actively stabilized members, and discusses potential industrial applications.

Introduction

Although structural materials such as steel are very strong in many ways, they have one severe flaw: they are flexible. When long, thin members are loaded in compression beyond a certain critical load, this flexibility leads to buckling, in which the member suddenly flexes due to the applied load. Buckling is a sudden failure that occurs without warning and often leads to complete structural collapse, requiring that very large safety factors (load reductions of 20x-100x) be incorporated into designs in order to ensure that buckling does not occur. Active control allows members to be loaded beyond their critical buckling load by using sensors to detect the onset of buckling motion and applying actuation forces to restore the member to the undeflected position.

In theory, a perfectly straight, unperturbed column will never buckle, and can support loads well above the critical buckling load. In practice, columns are never perfectly straight, and there is always some sort of disturbance going on. The key idea that makes active control of buckling attractive is that if the onset of buckling is detected very early, while the column is still nearly straight, the column will still be supporting almost all of the applied load. Thus the control forces do not need to support the applied load directly, but merely need to oppose disturbances and compensate for material imperfections.

Dynamics of Column Buckling

When the active control system is operating, the deflections of a column will be kept small. For small deflections the column dynamics are approximately linear, allowing dynamic behavior to be described as a sum of independent modal solutions, which are shown below using a coordinate system in which **y** denotes the deflection of the beam at each point and **x** denotes location along the length of the beam:

$$y(x,t) = \sum_{n=1}^{\infty} \phi_n(x) q_n(t)$$

Each modal solution consists of a function $\phi_n(x)$ describing the mode shape of the nth mode, and a function $q_n(t)$ describing how the amplitude of this mode shape varies over time. A column supported by pins at its endpoints has mode shapes that are sinusoidal, as illustrated in Figure 1. Although there are many modes in which columns can buckle, buckling in the first mode is the factor that limits how much load can be applied to a column, since the critical buckling load ($\mathbf{P_{critical}}$) for the first mode is lower than that of the higher modes (Equation 4).

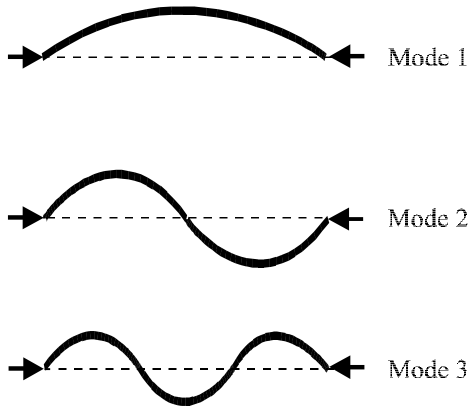

Figure 1: The first three mode shapes of a beam with pinned ends, as determined by Equation 1. The shape of the beam at any instant in time is expressed as a sum of mode shapes. The amplitude of each mode shape varies with time as determined by Equation 2.

The equation of motion and its solutions for a column with pinned ends for a column of length ***L*** having mass per unit length **γ**, modulus of elasticity ***E***, moment of inertia ***I***, and supporting a constant axial loading force ***P*** are:

$$\left(\frac{EI}{\gamma}\right)\frac{\partial^4 y}{\partial x^4} + \frac{P}{\gamma}\frac{\partial^2 y}{\partial x^2} + \frac{\partial^2 y}{\partial t^2} = 0$$

$$\phi_n(\mathrm{x}) = \sin\left(\frac{n\pi x}{L}\right) \quad (1)$$

$$\ddot{q}_n + w_n^2 q_n = 0 \quad (2)$$

$$w_n = \frac{n^2\pi^2}{L^2}\sqrt{\frac{EI}{\gamma}}\sqrt{1 - \frac{P}{P_{critical_n}}} \quad (3)$$

$$P_{critical_n} = \frac{n^2\pi^2 EI}{L^2} \quad (4)$$

where $\boldsymbol{w_n}$ denotes the natural frequency of mode ***n.***

Note that when a column is loaded above the critical buckling load, the frequency of vibration in that mode becomes imaginary (Equation 3). In other words, the column no longer has sufficient strength (stiffness) to overcome the bending moments being applied by the axial load. Unless an external control force intervenes, the amplitude of deflection in that mode will grow exponentially over time, leading to failure of the column. In theory (Equation 4), preventing buckling in the first mode will yield a factor of 4 increase in load-bearing strength, since the critical buckling load for the second mode (n=2) is 4 times larger than the critical buckling load for the first mode (n=1). Similarly, preventing buckling in each of the first two modes will (theoretically) result in a factor of 9 increase in strength. In practice, beams are never perfectly straight, but rather have some degree of built-in eccentricity, the direction and magnitude of which may vary along the length of the beam. Thus in the real world, a column will begin to buckle at loads somewhat smaller than the theoretical buckling load predicted by Equation 4.

Prior Approaches

There have been several theoretical studies of the differential equations governing column buckling that have indicated that active control of buckling can be achieved.[7,12,8,5] Meressi and Paden[8] showed analytically that piezoelectric (PVDF) actuators mounted continuously along the length of a column could be used to stabilize the first mode of column buckling, in theory achieving a factor of 4 increase in load-bearing capability. Chandrashekhara and Liu[5] showed via finite-element analysis that actuators mounted in the center of a compressed plate could increase its uniaxial buckling load by approximately 10%.

Jefferis[7] conducted an experiment in which an electromagnet was used to stabilize the first buckling mode of a column, effectively forming an electromagnetic restoring spring connected to an external brace. Berlin and Sussman[3] conducted an experiment in which the first buckling mode was stabilized through the use of externally-driven tendons acting on a yard mounted perpendicular to a column. Baz[1] developed a way to actively change the length of a column using Nitinol actuators, redistributing the load in a structure so as to keep supporting columns from being loaded above their buckling load. Baz[2] has also used Nitinol wires attached to external "ceiling" and "floor" supports to adaptively brace a column against buckling. In the smart structures field, extensive work has been performed on active control of vibration, but until recently little attention has been given to the possibility of controlling buckling for the purpose of increasing the load-bearing strength of a structure.

The experimental prototypes described in this paper differ from previously published work in that the use of induced-strain actuation allows active control of buckling to be achieved without the need for external braces, yards, or supports. In addition, these experiments represent the first time that multiple buckling modes have been actively stabilized simultaneously.

Design Considerations

The design of actively stabilized members involves a complex set of tradeoffs that can often be counterintuitive. Decisions regarding actuator placement, actuator sizing, and substrate material selection interact in complex ways with design constraints such as the desired load-bearing capability of the member, the allocation of control authority between modes, and the susceptibility of the system to external perturbations. After much experimentation with discrete-element simulations (described in Berlin[4]), we found that the following criteria were particularly useful for the purpose of summarizing design tradeoffs:

1. The *stabilization position*, which measures the maximum static deflection of the midpoint of the column at which sufficient control authority is available to counteract buckling. It is important that this maximum stabilizable deflection be large, because eccentricities and other imperfections tend to make the column act slightly deflected even when it is in its equilibrium position, and because external perturbations can increase the deflection of the column. In our design process, we used as our metric the stabilization position of the first buckling mode for a column loaded to 2x its critical buckling load.

2. The *control ratio*, which measures the relative size of the region in which the control system can operate. The control ratio is the ratio of the stabilization position (mentioned above) to the minimum deflection at which the onset of buckling can be detected. Ideally one would like the control ratio to be as high as possible, to provide the maximum amount of safety margin between the deflection at which buckling motion is first detected and the deflection beyond which buckling motion can no longer be prevented. In our design process we calculated control ratios based on a column loaded to 2x its critical buckling load, with an estimate of the minimum detectable first-mode deflection being that which results in 20 μstrain at the midpoint of the column (which in retrospect was overly conservative).

3. The *buckling load* of the composite beam.

4. The distribution (spillover) of actuation authority between the various modes. Spillover of actuation authority is undesirable both because it diverts actuation authority away from the unstable buckling modes and because it can induce undesirable vibrations. We measured spillover by plotting the maximum static modal deflections that the actuators can induce in an unloaded column.

These design metrics summarize the complex interactions that occur when multiple design factors come into play simultaneously. For instance, given a design target for the thickness of piezo-ceramic actuator to be used, as well as a target buckling load, consider the factors that go into choosing a material for the core substrate on which the piezo-ceramic actuators are to be mounted: Choosing a more flexible substrate material requires that a thicker beam be used to achieve the buckling load. Use of a thicker beam in turn gives the piezo-ceramic actuators more leverage by moving them farther from the center of the column, thereby increasing the moment that can be achieved through piezo-ceramic actuation. However, moving the piezo-ceramics farther from the center of the column also increases the relative effect of the actuators themselves on the stiffness of the system. In addition, use of a thicker substrate allows more accurate measurement of curvature, since the strain gages are mounted on the surface of the substrate, and a thicker substrate will undergo more surface strain for a given curvature than will a thinner substrate.

Figure 2 presents an example of the use of these metrics to summarize the design tradeoffs associated with material selection for a 12 inch long composite column. For instance, a column using a .010" thick fiberglass substrate has a larger stabilization position than does a column that uses a thicker (0.030") fiberglass substrate, and is thus less sensitive to eccentricities than the thicker column is. However, the 0.030" thick fiberglass provides a larger control ratio than does the 0.010" fiberglass, since the increased thickness of the substrate increases the ability of the sensors to detect the onset of buckling. We chose 0.010" thick steel for our experiments because it provides both a high control ratio and a relatively large stabilization position, while still providing sufficient stiffness to support substantial loads. (In addition, spring steel has the advantage of being resistant to taking a "set" (e.g. undergoing plastic deformation), a factor which permits the prototype column to be reused once it has been permitted to buckle.)

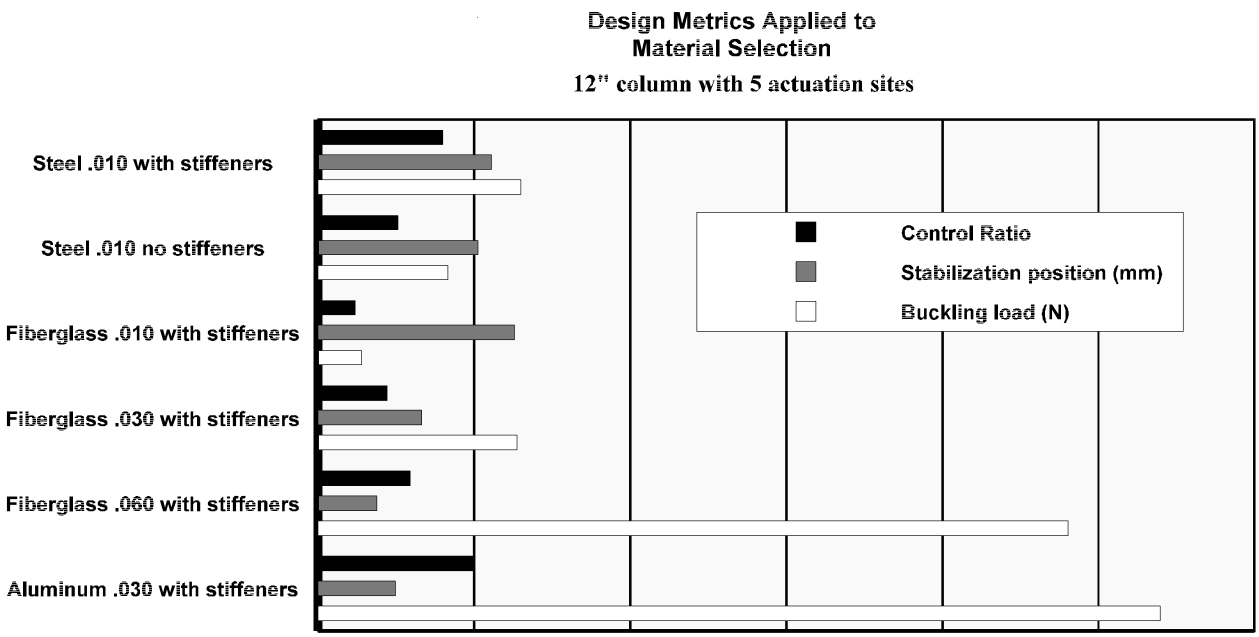

Figure 2: Substrate Material Selection Tradeoffs. This chart illustrates the tradeoffs that arose when selecting a suitable substrate material and thickness for use in the piezo-ceramic composite column. Note that the .010" thick steel column that includes stiffeners mounted in the gaps between adjacent actuators has a larger stabilization position and control ratio than the steel column that does not have stiffeners. The addition of the stiffeners prevents local bending in the gaps, redirecting actuation authority towards the first mode. This redirection of actuation authority allows the column with stiffeners to make better use of its actuation forces, achieving a larger stabilization position even though it has a higher buckling load (and hence requires larger restoring forces) than the column without stiffeners. (The control ratios and stabilization positions shown are for a column loaded to 2x its critical buckling load, with a minimum detectable deflection of 20 μstrain at the midpoint of the column.)

Active Column Experiment

Structure of the Composite Column

Active control of buckling has been demonstrated using a composite column that is actively stabilized against buckling through the use of piezo-ceramic (PZT) actuators. This column, which is pictured in Figure 4, achieves a factor of 5.6x increase in load-bearing capability through active stabilization of the first two buckling modes. The column is 12.6 inches in length and has a theoretical buckling load of 9 Newtons. In practice, buckling occurs at a load of 5.27 Newtons, which is somewhat less than the theoretical buckling load due to eccentricity and other small imperfections in the material and support structure of the column. The onset of buckling is detected by an array of strain gages mounted along the length of the column. Forces that counteract buckling motion are supplied by an array of piezo-ceramic actuators.

Actuation is achieved using the induced-strain method, in which actuators are mounted in pairs on each side of the column and are driven out of phase so that the actuator on one side of the column seeks to grow, while the actuator on the other side seeks to shrink, thereby applying a distributed bending moment to the column. The composite column is constructed from a base material of 0.010 inch thick spring steel, 12.6 inches long and 2 inches wide. A total of 10 piezo-ceramic actuators are mounted on the column in pairs, with 5 actuators on each side. Each actuator consists of a rectangular 2 inch long, 1.5 inch wide, 0.010 inch thick piece of nickel-plated lead-zirconate-titnate (PZT), a piezo-ceramic material, embedded in a polyimide flex-circuit.

Due to manufacturing constraints there is a gap of approximately 1/4 inch between adjacent actuators. Early in the design process, finite-element simulations indicated that local bending would occur in the gaps between the actuators, since that region is more flexible than the rest of the column. This localized bending caused a spillover of actuation authority into the 5th and 11th vibrational modes, dramatically reducing the influence of the actuators on the first and second modes. To prevent localized bending, small 0.010 inch thick steel plates that act as stiffeners are mounted in the gaps between adjacent actuators, as illustrated in Figure 3.

As pictured in Figure 4, each end of the column is held in place by a pinned end-support. The end-support consists of a hinge constructed using low-friction stainless steel ball-bearings encased in an anodized aluminum housing, which provides a nearly ideal pinned end-condition. The column itself is mounted in a test jig that applies a compressive load using a rod held in place by a linear pillow-block assembly. The pillow block ensures that the load force is directed parallel to the column. An aluminum clamp mounted above the pillow block acts as a limit stop, preventing total collapse of the column when buckling occurs.

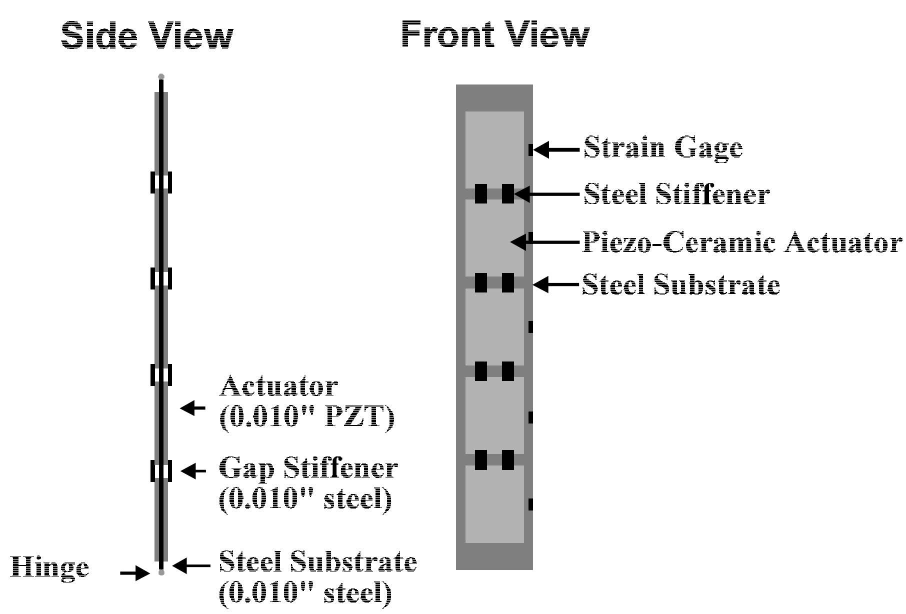

Figure 3: Front and side views of the composite steel/piezo-ceramic column. The column is 12.6 inches in length. Steel stiffeners are used to increase the stiffness of the area between adjacent actuators that is not covered by piezo-ceramic material.

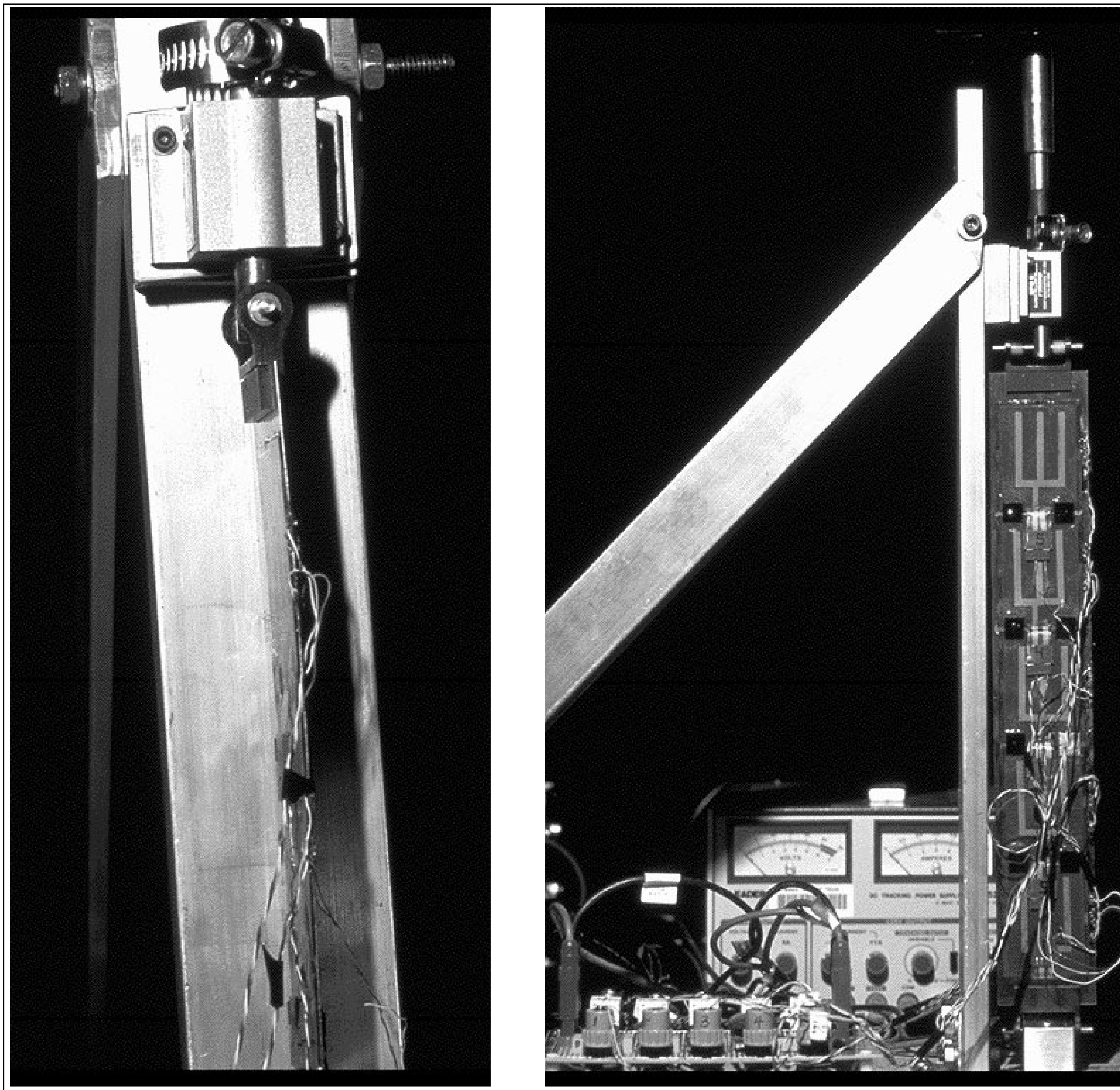

Figure 4: Photographs of actively stabilized column. Active control enables this column to support 5.6x more load than would otherwise be possible. An array of strain gage sensors mounted on the column detect the onset of buckling. Piezoceramic actuators apply actuation forces that counteract buckling motion. The axial load is applied through a linear pillow-block assembly. Each end of the column is pinned by a hinge joint constructed from low-friction ball bearings. A screw clamp mounted above the pillow block assembly acts as a limit stop to prevent total collapse of the column when buckling occurs.

Control Strategy

Active control was applied only to the first two buckling modes, since the higher modes are inherently stable over the range of loads being applied to the column. The control strategy is implemented by a centralized control computer (a 486 PC), which is fed information about the column's dynamic behavior by five pairs of resistive strain gage sensors. The control computer interprets all five strain readings to produce an estimate of modal amplitude for the first and second mode. A non-linear variant of PID control operates on the modal amplitude data to determine the appropriate control actions to take to stabilize each mode. This modal approach enables the control system to distinguish curvature changes associated with buckling in the first two modes from curvature changes associated with higher-order mode vibrations. The first and second buckling modes are treated as being independent of one another, and are controlled by independent controllers.

Control of the first buckling mode is achieved through the use of all five pairs of piezo-ceramic actuators acting in parallel. The actuators located near the midpoint of the column are excited using a higher voltage than the actuators near the ends of the column, so as to match the relative magnitudes of the bending moments associated with the first mode. To actuate the second mode, the topmost two pairs of actuators are driven in one direction, while the bottommost two pairs of actuators are driven in the opposite direction. The center actuator pair was not used for actuation of the second mode, since it lies partially in the top half and partially in the bottom half of the column.

Each mode is controlled by a variant of a P.I.D. (**P**roportional + **I**ntegral + **D**erivative) control strategy that I refer to as **PD+IV** control. I developed this variant based on experimental observation in order to overcome problems associated with sensor noise, built-in eccentricity of the column itself, and hysteresis in the piezo-ceramic actuators. The final form of the control law includes terms that operate at two distinct time scales to allow the response to high-frequency perturbations to be specified independently of the response to low-frequency, longer-lasting effects. For *each* mode, the control action is computed as follows:

$$\text{Control Action} = \Big((\mathbf{P} * \textit{position}) + (\mathbf{D} * \textit{velocity}) + (\mathbf{I} * \textit{long\_term\_position}) + (\mathbf{V} * \textit{long\_term\_velocity}) \Big)$$

The controller works by using the proportional term (**P**) to counteract small high-frequency disturbances in the vicinity of the equilibrium point. The short time-scale derivative term (**D**) provides damping that helps to prevent overshoot and to ensure that oscillations associated with proportional feedback will die out. The integral term (**I**) is used to provide a long-term offset that corrects for eccentricity in the column, for hysteresis in the piezo-ceramic actuators, and for offset of the controller's target position from the true equilibrium position of the column. A long time-scale derivative term (**V**) acts to damp out oscillations induced by the integral feedback. To prevent the controller from reacting to measurement noise when the column is in the vicinity of the equilibrium position, the controller includes both position and velocity deadbands.

Experimental Results

By controlling both the first and second buckling modes, the active column was able to support a load of 29.88 Newtons, a factor of 5.6 times greater than the experimentally observed uncontrolled buckling load of 5.27 Newtons. The system was able to withstand external perturbations, as illustrated in Figure 5. When the column was loaded above 29.88 Newtons, failure occured in the second buckling mode. Even after failure occured and the rod applying the load had fallen down to the limit-stop, the first mode remained controlled, with the column coming to rest in an “S” shape characteristic of the second buckling mode. Only after the controller was turned off did the column return to its first-mode shape.

The primary factors preventing the column from supporting even more load were measurement noise and limited control authority. The limited control authority is partially due to the placement of the actuators, which is such that the centermost actuator cannot be used to actuate the second buckling mode. Figure 6 shows a phase-space plot of the controlled system. The plot clearly shows that the controlled system contains two stable fixed points, one on either side of the unstable equilibrium position. In other words, measurement noise prevents true stabilization of the system, leaving the zero deflection point unstable and creating two stable fixed points located at very small deflections to either side of the zero deflection point. If measurement noise was reduced, the two stable fixed points would move closer to the equilibrium position. From the perspective of minimizing the impact of externally applied perturbations, the best behavior was obtained when the controller was tuned to keep the column in the vicinity of one of the attractors. I suspect this biasing of the control system was effective because it allowed the control system to avoid problems (such as integrator wind-up) that can occur when traversing an unstable equilibrium point.

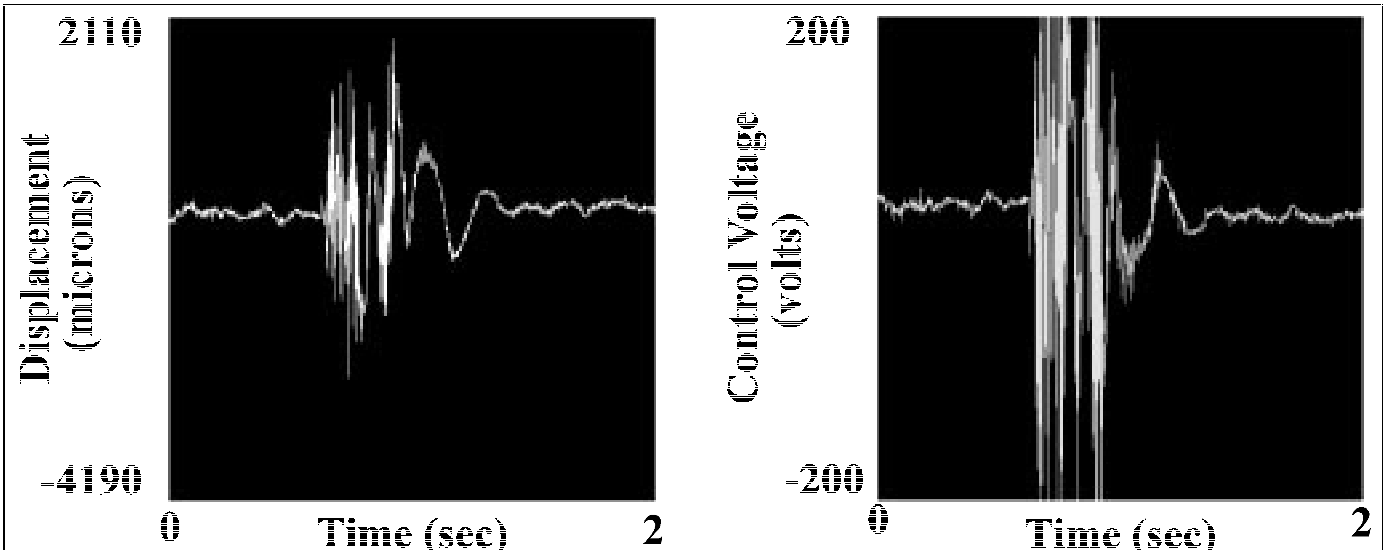

Figure 5: Response to perturbation. The plot on the left shows the 1st-mode deflection of the midpoint of the column vs. time. The plot on the right shows the control voltage applied to the center actuator vs. time. The perturbation was induced by banging my fist on the table as hard as I could.

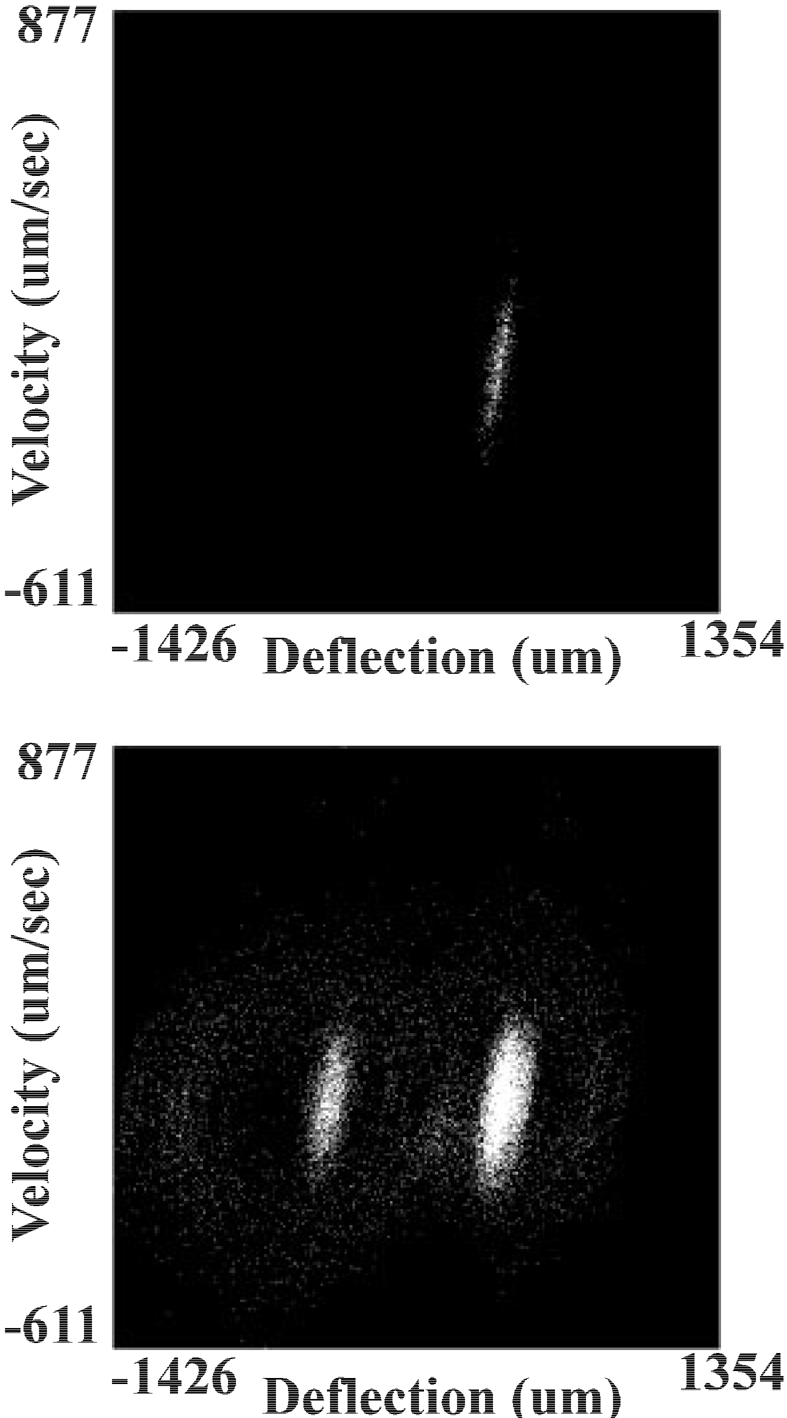

Figure 6: Phase plots of the system in operation. The top plot shows the velocity vs. position of the system during normal operation. The bottom plot shows the velocity vs. position of the system undergoing oscillations. This view was created by artificially adjusting the control law so as to induce oscillations that would depict the structure of phase space.

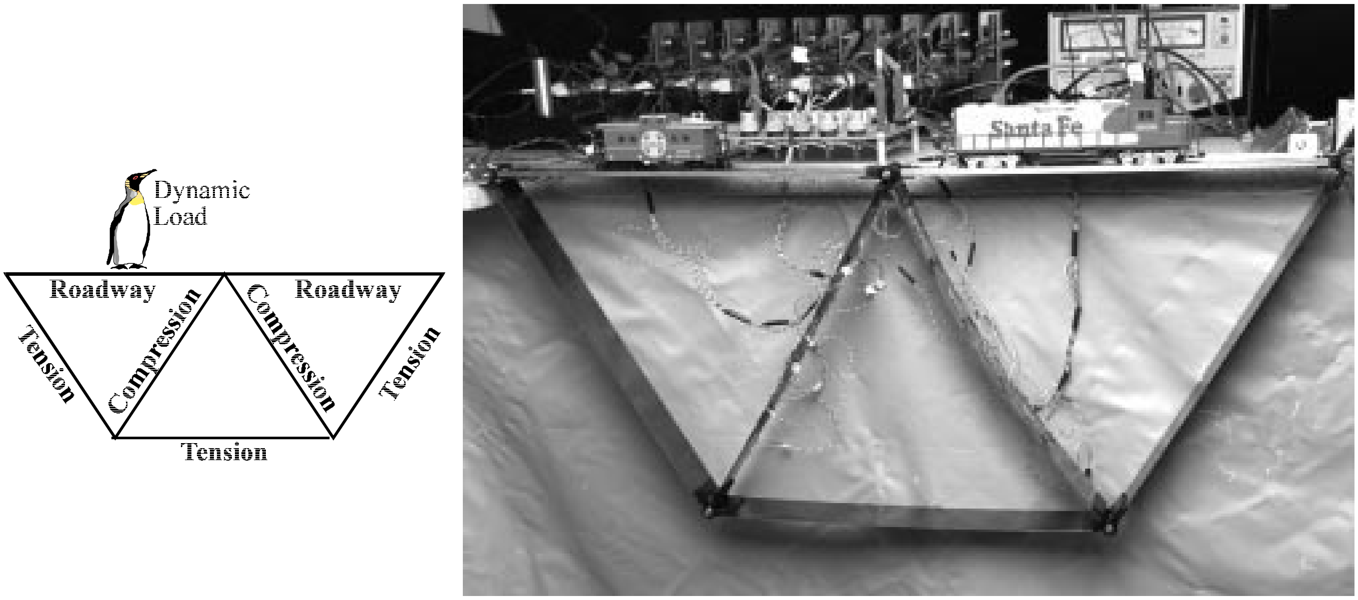

Figure 7: Actively stabilized truss bridge. This bridge incorporates two compressive members that actively resist buckling.

Active Bridge Demonstration

Compound structures have interactions that are complex and troublesome to model, making it difficult to predict how control actions taken to prevent buckling of one member will influence the other members in a structure. Indeed, it is conceivable that the various active members in a structure could act as coupled oscillators, creating system-level dynamical instabilities similar to those that can arise due to the wind-induced pumping of energy into the vibrational modes of a structure. Will it be possible to use independent, local strategies to control each active member, or will it prove to be essential that the various active members in a structure communicate with one other to coordinate control actions?

To explore the behavior and interactions among multiple active members in a structure, and to investigate the destabilizing effect of gravity on actively controlled beams, we experimented with a small-scale railroad-style truss bridge that incorporates two compressive members that actively resist buckling. This bridge, pictured in Figure 7, is composed of steel/piezo-ceramic composite beams identical in structural design to the piezo/steel composite column described earlier. Each active member has its own dedicated control computer (running the PD+IV control strategy) and is controlled entirely independently of the other active beam in the structure. Although the bridge design called for the compressive members to be identical, one of them turned out to be stiffer than the other. (Due to the limited availability of the 0.010" thick piezo-ceramic material, the second member was fabricated using slightly thicker 0.012" thick piezo-ceramic actuators.) As a consequence, the compressive member shown on the left in Figure 7, which has a buckling load of 11.7 Newtons, is somewhat stiffer than the compressive member on the right, which has a buckling load of only 9 Newtons.

The truss bridge worked well, with no significant interaction between members observed. A series of external perturbations were applied by hand, by bouncing a finger near the center pin joint on the roadway. For loads (here "loads" refers to the force applied to the center pin joint of the bridge) below 20.9 Newtons, both active members responded well to the perturbations. The factor that limited how much load could be placed on the bridge was the ability of the thinner active member (the right one) to resist external perturbations, primarily due to a reduction in the *stabilization position* caused by the influence of gravity on the very thin beam. Indeed, when the active control system is turned off, the members visibly sag under their own weight.

The active truss bridge demonstrates that it is possible to combine multiple actively stabilized members to form a compound structure. However, further research is required to determine under what conditions the active members in a structure can be controlled independently, and what degree of communication and coordination is desirable between the controllers of different members.

Potential Applications

Extended Lifetime

One potential application for active control of buckling is to extend the lifetime of equipment by reducing fatigue. For instance, in a phenomenon known as wave-induced whipping, compressive members supporting the hulls of large ships buckle in heavy sea conditions due to wave action pounding on the hull.[6] Fortunately, the duration of the forces applied by a wave is (usually) short enough that buckling does not progress to the point of causing the immediate failure of the member. However, after repeated loading cycles, the buckling motion causes metal fatigue which damages the member over time, leading to very high maintenance costs. Active control would counteract the buckling motion induced by the wave action, thereby preventing buckling-induced metal fatigue. Industrial equipment that undergoes periodic large compressive loads is another potential target for active fatigue reduction.

Strength on Demand

One of the most important potential applications for active control of buckling is to supplement traditional designs, providing an added factor of safety in the form of "emergency strength" for exceptional situations. For instance, when an airplane makes an unusually hard landing, the landing struts could be given added strength by actively controlling buckling. Aircraft are particularly attractive candidates for this technology because they already have highly reliable sources of power, have hydraulic and electrical systems available for actuation, and undergo large dynamic loading only for brief periods.

In some applications it may even prove feasible to rely on active control to support ordinary loads. For example, the speed and range of a missile could be extended by reducing its weight through the removal of material from its fuselage or engine housing, compensating for the resulting strength reduction by using active control to withstand periods of high load. Similarly, the engine housings of fighter aircraft could be actively stabilized against buckling during the high compressive loads encountered during full power dives, perhaps using aerodynamic appendages or fuel jets as actuators.

In 1970 an architect, William Zuk, predicted that some day mankind would learn to control the buckling of columns and would use this technology to build a city on top of an existing city, supported by very tall and slender actively stabilized columns.[12] Although the civilian economy is probably not yet ready for the idea of buildings that fall down when you switch them off, there are nevertheless potential applications in civilian buildings. One possibility would be to increase the strength of compressive members so as to make them better able to resist earthquake-induced dynamic loads. However, a potentially more important aspect of active control of buckling is that it provides a structural designer with a new option: a compressive member that can actively be made strong during normal operation to provide resistance to wind-induced vibration, but which can be allowed to flex during an earthquake to allow the structure to sway in response to the quake.

Portable/Deployable Structures

Active control of buckling has the potential to create structures that are both stronger and lighter than would otherwise be possible. This has the potential to enable ultra lightweight structures, such as a portable bridge that could be carried in a backpack or jeep and yet be strong enough to carry heavy loads. Other potential infrastructure related applications include portable telescoping supports for temporary reinforcement in the aftermath of disasters such as earthquakes and hurricanes.

Moving Flexible Objects

Industrial applications that require the high speed precision movement of flexible objects are frequently plagued by the buckling of the objects being manipulated. A potential industrial application of this technology would be to use remote sensing and actuation approaches to actively sense the dynamical state of the object being manipulated and to apply control forces that prevent it from buckling.

Conclusions and Suggestions for Future Work

This experiments presented in this paper clearly demonstrate that compressive members can be stabilized against buckling without the use of external braces or supports, that multiple buckling modes can be actively stabilized simultaneously, and that it is possible to incorporate multiple actively stabilized members into a structure without inducing undesirable interactions. Nevertheless, much work remains before we reach the point where it is practical to embed active dynamical control components in objects on as routine a basis as we now make use of ordinary paint.

One of the primary factors limiting the performance of the prototype columns was limited sensor accuracy, particularly with regard to the measurement of velocity. While the resistive strain gages used as sensors provided direct measurements of column shape, the velocity estimates derived from these measurements were relatively noisy. In contrast, materials such as PVDF film provide highly accurate measurements of shape *changes*, but do not provide an absolute measurement of shape. One possible direction for future work would be to use both velocity sensing mechanisms, such as PVDF, and shape-measuring devices, such as strain gages, to provide low-noise measurement of both position and velocity. Another possibility would be to use semiconductor or MEMS-based strain gages, which are more accurate than resistive strain gages.

Another possible direction for future work, particularly in the domain of constructing larger-scale structures, would be to experiment with alternative actuation strategies. Although the use of piezo-ceramics to apply bending moments to a member is attractive for small-scale structures, such as laboratory prototypes, for larger-scale structures it may prove more practical to use electromagnetic effects to supply the forces required to counteract buckling. One possibility worth investigating would be to use electromagnetic motors to drive tendons that pull on anchor points to induce strain in a member.

The control strategies used to control the prototype columns were basically “off-the-shelf” control strategies that were not based on knowledge about the dynamics of the system being controlled. For instance, the P.I.D. control strategy seeks to slow down the column even if it is moving in a desirable direction. A model-based control strategy along the lines of that suggested by Zhao,[11] which takes the inherent dynamical behavior of the column into account, holds the promise of being better able to control dynamical behavior. Another possibility would be to experiment with adaptive control strategies that observe the behavior of the system and automatically adjust the control law parameters to eliminate undesirable behavior patterns. We also need ways of analyzing the range of perturbations an actively stabilized system can withstand, e.g. how will an actively stabilized bridge react when a truck hits a pothole?

Although the actively controlled truss bridge shows that it is possible to incorporate multiple actively controlled members into a structure, it does not tell us under what circumstances this will be possible. A design approach needs to be developed to address the structure-level issues associated with the interactions between actively controlled members and the structures in which they are embedded. One possible direction would be to develop control strategies that take into account, or even take advantage of, the interactions among the active members. Such a control strategy could be centralized, requiring that a data network interconnect the various structural elements. Another possibility would be to use purely local control strategies, in which each member is controlled individually using local information. Through clever design, these locally controlled elements could produce globally desirable behaviors, either by using the dynamical behavior of the structure itself to communicate with one another to coordinate actions, or by using techniques for generating complex large-scale behaviors from locally acting agents.

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References

1. A. Baz and L. Tampe, "Active control of buckling of flexible beams," *Proceedings ASME Design Tech. Conf. (Montreal, Canada, 1989)* vol DE-16, New York:ASME pp 211-218.

2. A. Baz et. al., "Active buckling control of nitinol-reinforced composite beams", *Active Materials and Adaptive Structures*, Proceedings of the ADPA/AIAA/ASME/SPIE Conference on Active Materials and Adaptive Structures, 4-8 November, 1991, Alexandria, Virginia. Published by the Institute of Physics Publishing.

3. A. A. Berlin and G. J. Sussman, "Increasing the Compressive Strength of a Column via Active Control", *Third International Conference on Adaptive Structures*, San Diego, CA. 1992

4. A. A. Berlin, *Towards Intelligent Structures: Active Control of Buckling*, Ph.D. Thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 1994.

5. K. Chandrashekhara and K. Bhatia, "Active buckling control of smart composite plates - finite-element analysis", *Smart Materials and Structures*, (1993) 2, 31-39.

6. S.R. Heller, Jr. and J.T. Kammerer, "Buckling of Long Slender Ships due to Wave-Induced Whipping", *Dynamic Stability of Structures*, ed. G. Herrmann, Pergamon Press, 1967 pp 129-156 (Conference took place October 18-20, 1965)

7. R. P. Jefferis, *Feedback Control of the Buckling Instability in an Axially Compressed Thin Elastic Beam*, Ph.D. Thesis, Department of Electrical Engineering, University of Pennsylvania, 1968. Available from UMI Dissertation Services, Ann Arbor, Michigan.

8. T. Meressi and B. Paden, "Buckling Control of a Flexible Beam Using Piezoelectric Actuators", *Journal of Guidance, Control, and Dynamics*, Sept-Oct 1993 v16(5), pp 977-980.

9. M. Paz, *Structural Dynamics: Theory and Computation*, New York:Van Nostrand Reinhold, 1991.

10. W.C. Young, *Roark's Formulas for Stress and Strain*, McGraw Hill 1989

11. F. Zhao, "Phase Space Navigator: towards automatic control synthesis in phase spaces for nonlinear control systems", *Proceedings of the 3rd IFAC Workshop on Artificial Intelligence in Real-Time Control*, Oxford UK: Pergamon 1991.

12. W. Zuk and R. Clark, *Kinetic Architecture*, New York: Van Nostrand Reinhold Company, 1970.