Stress-Strain Plots as a Model of an Organization's Resilience

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Abstract. Ways to characterize and measure an organization's resilience can be based on an analogy from the world of engineering: that of the relationship between stress—the load on a mechanical structure, and the resulting strain—how the structure stretches in response. Cognitive Systems Engineering already has suggested that to characterize a system one should examine how the system responds to different demands for work. Stress-strain plots, or for organizational resilience, demand-stretch plots, provide a way to characterize the properties of the organization as an adaptive system. This includes different regimes—a **uniform** region where the organizations stretches smoothly and uniformly in response to an increase in demands; and an **extra** region (x-region) where sources of resilience are drawn on to compensate for non-uniform stretching (risks of gaps in the work) in response to increases in demands. Organizations are often mis-calibrated as to how they actually operate: concluding that behavior is occurring well within the uniform region, when the organization often is actually operating in the x-region given the demands faced. The parameters associated with different aspects of stress-strain relationships can be seen as the parameters to be estimated to characterize an organization's ability to adapt as demands change.

1 INTRODUCTION

In Cognitive Systems Engineering, demand factors are critical (Woods, 1988). Understanding how the joint system responds to types of demands or to changes in demands reveals how that system functions. Woods & Patterson (2000; cf., also, Woods & Hollnagel, 2006, chapter 9) used this idea to propose that one should evaluate and predict system performance by relating how demands increase and cascade to the ability of the joint system to bring more knowledge and expertise to bear. In effect, they suggested mapping how demands increase relative to how the joint system stretches to accommodate the increasing demands (tempo, cascade of effects, and the potential for bottlenecks).

The discussions following from the first symposium on Resilience Engineering (Hollnagel et al., 2005) often used language related to how an organization stretches as demands increase. This triggered the thought that an analogy to stress-strain plots in material science could stimulate development of a model to plot and measure an organization's resilience. This paper pursues this analogy and suggests how it might be used to define parameters which would characterize how organizations adapt to increasing loads or demands. It also provides a framework for understanding how some already developed measurement techniques and tools can be used to assess when the stretching process may be reaching a critical point.

2 THE ANALOGY: STRESS-STRAIN PLOTS

2.1 Regions in Stress-Strain Plots

The starting point is to recognize that we want to assess how an organization responds to an increase in load or demands. This is the y-axis or the stress axis in a stress-strain plot for a material. We will label the y-axis in our analogy the demand axis (D) and the basic unit of analysis is how the organization responds to an increase in D (actually, an increase in D relative to a base level of D) (Panel a of Figure 1). The y-axis then captures how the material stretches when placed under a given load or a change in load. In the analogy, the y-axis captures how the organization stretches to handle an increase in demands (S relative to some base stretched point).

In materials there are two different regions of behavior: the elastic region where the material stretches uniformly under increasing load and a plastic region where the material begins to stretch non-uniformly until the distortions and gap accumulate and a fracture or failure point is reached. In the elastic or uniform region the response to increasing demands is linear; in the plastic region the material cannot stretch completely to meet the demand (Panel b of Figure 1).

In the first region—which we will term the uniform response region—the organization has developed plans, procedures, training, personnel that can stretch uniformly as demand varies in this region. This is the on-plan performance area or what Woods (2006) referred to as the competence envelope. Note the analogy provides two parameters associated with uniform region: its slope and its length before the transition to the second behavior region.

Fig. 1. Stress-strain or demand-stretch plot. The first region is marked by a linear relationship whereby the system stretches smoothly and *uniformly* to increases in demand (Panel a). In the second region, increasing demands leads to more than linear stretching, denoting gaps which must be compensated for less the system begin to approach the failure point (Panel b).

In the second region non-uniform stretching begins; in other words, 'gaps' begin to appear as the change in demands exceeds the ability of the organization to adapt within the competence envelope (the limit of the first order adaptations built into the plan-ful operation of the system in question). To avoid an accumulation of gaps that would lead to a system failure, active steps are needed to compensate for the gaps or to extend the ability of the system to stretch in response to increasing demands. These local adaptations are provided by people and groups as they actively adjust strategies and recruit resources so that the system can continue to stretch. We term this the 'extra' region (or more compactly, the x-region) as compensation requires extra work, extra resources, and new (extra) strategies. These local adaptations draw on sources of resilience to provide the extra adaptiveness the system requires to function under increasing demands without gaps accumulating to the failure point. This process continues to cope with increasing demands until either the second-order sources of adaptiveness are exhausted and the system reaches a failure point (the decompensation pattern in Woods and Cook, 2006) or until the system re-organizes and functions in a new uniform mode.

Thus, there is a third region where the system re-structures into a new form with a new slope and length of uniform or on-plan performance in its new mode.

2.2 Limits to the Analogy

The most obvious limit on the analogy with materials is that for systems the process of stretching in response to increasing demands is an active process, both in the uniform region as stretching represents the adaptive capacity of the on-plan behavior and in the x-region as people actively adapt to inject new resources and strategies to stretch adaptive capacity further.

The second difference is that the system can reorganize in response to increasing demands to take on a new form with new ways of functioning. One simple example is the plan for an Emergency Department to shift should a mass casualty event occur (Perry et al., 2006; Wears & Perry, 2006).

The third difference is that a connection can exist such that as an organization is successful more may be demanded of it ('faster, better, cheaper' pressures) pushing the organization to handle demands that will exceed its uniform range.

The fourth difference is that the system can pick up on signs that it has moved into the x-region. Recognizing that this has occurred (or is about to occur) leads people in various roles in that system to begin to adapt to make up for the non-uniform stretching. The need for X-adaptation can be anticipatory or it can occur after signs of gaps appear.

The fifth difference is that organizations, groups and people have models of their own capabilities and performance levels. These models can be well-calibrated or miscalibrated as organizations can think they are operating in the uniform region when the system is frequently challenged beyond the extent of the uniform region and has to draw on sources of resilience to continue to accommodate increasing demands.

3 CALIBRATION & MEASUREMENT

3.1 Calibration

Calibration here refers to how accurate is one's model of one's own performance or capability. A basic finding about resilience/brittleness is that organizations and distant observers are miscalibrated, that is they overestimate the capability of on-plan behavior to handle the situations and disruptions that can arise. This is captured very economically in the analogy to stress-strain behavior as the distant observer believes the transition line between the uniform region and the x-region is much further to the left on the x-axis than is actually the case (Figure 2).

In addition, organizations are often mis-calibrated about the parameters of the system in the uniform region overestimating the slope and the length of this region. In other words, they can mis-represent capabilities of on-plan behavior to meet demands and they can mis-represent the demands that will occur and how they would challenge on-plan behavior.

Overall, the organization or other observers of the organization can be well-calibrated or mis-calibrated with respect to any or all of the parameters associated with stress-strain plot for that organization.

The difficulty in staying calibrated to the actual state of a system's adaptive behavior arises because of the inherent difficulty discriminating when the system is near the transition zone between the uniform and x-regions.

3.2 Measurement

It is possible to use measurement techniques to provide ways for organizations to calibrate themselves though obtaining information about the onset of evidence of organizational strain. Evidence of compensations being needed to accomplish the goals and mission, or more simply, evidence of failures to provide compensation with the resultant losses in effectiveness can indicate when the organization is departing from the uniform region and moving into the x-region.

Such tools have been discussed elsewhere (Wreathall, 2006; Wreathall & Merritt, 2003; Wreathall, 2001), and their development is partly based on work going back to the late 1980's (e.g., Wreathall, Appignani, et al., 1990). However, with the development of resilience engineering, and more particularly the view described here, it is clearer what these tools accomplish. Specifically by investigating what are the current types of performance problems being faced by the functional groups and teams, and *how they are changing over time*, it is possible to detect significant changes in demands and performance. For example, by trending the kinds of problems being faced from deficiencies in (for example) paperwork and procedures, an upsurge can be detected in these problems that is likely to indicate a stretching of resources and the need for workers to adapt to the problems as described above. By selecting key activities for such monitoring, and using data-gathering tools that do not impose an additional burden on the workers who must also cope with the additional work demands, the potential onset of the transition to the x-region can be anticipated by the system's own management and resources or other responses provided in sufficient time and quantity to prevent further progression into the x-region, as discussed below.

4 RESILIENCE: RECOGNIZING AND MAKING TRANSITIONS

Moving from uniform response requires some actors in the system to recognize the emerging shortfall as demands increase or change from some base. These people in various roles initiate adaptations as they draw on sources of resilience. For example, an individual might adapt their strategies and utilize other resources to make up for an adaptive shortfall. Or a key person might recognize the shortfall and redirect a team of people to handle the evolving situation. With still higher demands the group as a whole might recognize the shortfall and adapt as unit to stretch with demand. In this way, the x-region is made up of a series of adaptive stretches: any one adaptive shift can become exhausted with the danger of decompensating toward a failure point; agents can recognize the shortfall and risk and initiate another adaptive shift. Panel b of Figure 2 illustrates 2 such shifts. Anders, et al., (2006) describe this kind of sequence within the emergency department as demands increase. Note that each shift in the x-region also relates to where control of the resources recruited lie: within an individual's control; within a team's control; within a unit. Going outside one's range of control may necessitate restructuring as some parts of the organization may have to permit or authorize changes in how resources are controlled and released to various actors/roles (as occurs in hurricane emergency response).

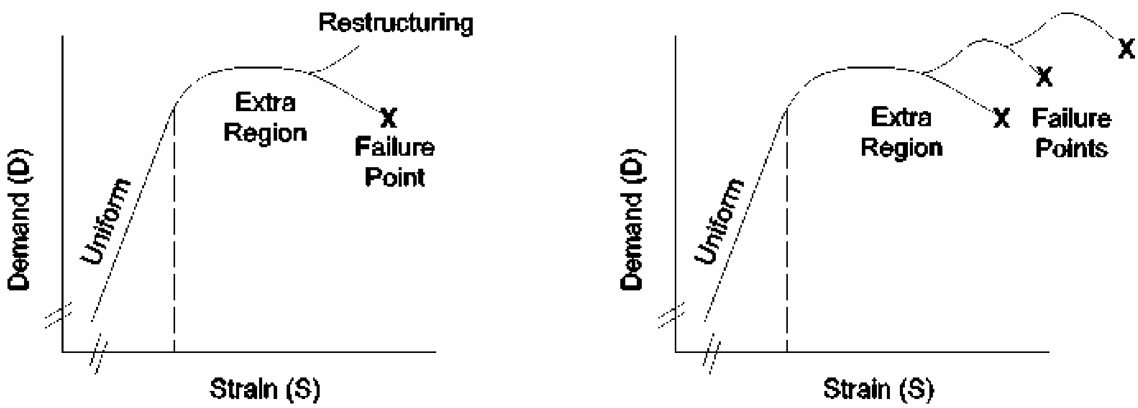

Fig. 2. People in various roles recognize signs the system is moving into the x-region (plastic region for materials) and these people initiate resilient adaptations (Panel a). But this adaptive behavior in the x-region can become exhausted and the system degrades toward a new failure point. The x-region can be made up of a series of resilient adaptive responses (Panel b shows 2). If stresses continue to increase the system may shift into a new form through restructuring. The ability to shift into restructured system as demands increase may depend on the how the system practices handling the transitions between regions.

If stresses continue to build, the system may shift to a new form through restructuring. A critical factor for resilient organizations may be how much the organization practices recognizing shortfalls and making transitions. Studies of mission control as a successful adaptive organization strongly suggest this conclusion (Patterson et al., 1999). Note that the transitions within the x-region and from x-region to a re-structured form have to be planned for and practiced in general as the specific situations are too varied and potentially unique.

One can think about the relationships in terms of the costs associated with stretching in response to demand changes. In the uniform region the marginal cost of stretching ($\Delta c/\Delta d$) is very low or near zero (the costs are built into the on-plan structure). In the x-region, the marginal cost of stretching is real and increases as demands increase (as cognitive or physical resources have to be recruited and deployed to compensate for the limited ability to stretch which are no longer available for other tasks). Our initial thought is that the cost of stretching in the x-region goes up as a series of steps that correspond to the shifts in range of adaptive response (two are shown in panel b of Figure 2). For example, in the hospital emergency department there is a cost associated with an individual in a role adapting (and therefore using various kinds of cognitive and physical resources), a different but higher cost for a group or team adapting and a further different/higher cost associated with an entire unit adapting as demands increase. Shifts in the cost associated with stretching in the x-region may be the key marker for the series of adaptive responses that can make up the x-region.

5 DISCUSSION

There are additional aspects of the analogy to discuss and there are additional parameters to help characterize organization's adaptive capacity suggested by the analogy. But a couple of points will suffice for this initial introduction of the stress-strain model.

Resilient organizations work to be well-calibrated despite change. This means such organizations exert effort at overcoming the uncertainties and difficulties in estimating the parameters captured in stress-strain plots.

Resilient organizations practice transitions in the face of increases in demands: (a) from uniform to x-region; (b) from individual to team to unit in the x-region; and (c) from x-region to a restructured form.

The same resource may be seen as an inefficiency from the perspective of behavior in the uniform region and yet be a part of how the system adapts to overcome shortfalls in the x-region. The relationship between extra resources when the system is in uniform range and extra resources in the x-region needs to be explored. Nevertheless, adapting in the x-region requires resources.

There are costs associated with recruiting resources and other parts of the organization may constrain or even resist releasing those resources. Plus taking resources for adaptive responses consumes them with respect to other activities. The stress-strain analogy suggests some ways to model the costs associated with bringing resources to bear.

5.1 Caveats

This introduction does not address the design problem—how to set up or modify an organization to be more resilient across the parameters captured in stress-strain relationships.

The stress-strain model has limits. One notable one is that all demands are mapped onto a single dimension when there are clearly different kinds of demands that disrupt on going plans in different ways and that challenge adaptive capacity in different ways.

Our exploration of the stress-strain analogy has proven very promising. But the ultimate test for this (or any) way to model/measure resilience is whether it can show management how resources that would otherwise look like an inefficiency to be squeezed out is actuality part of what makes the system resilient in the transitions between regions as demands require adaptation.

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