Concrete Practices: Testing in an Earthquake Engineering Laboratory

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Abstract

Successful testing depends upon making a projection from a test situation to the performance of a technology under working conditions. Some have argued that projection is made possible primarily through a collective agreement that these two circumstances are similar in certain crucial ways. This paper argues that projection can be better understood, in many cases, as a set of local processes through which the practices of testing are made to produce change in a wider context of technological practice. In the earthquake engineering laboratory described here, this connection depends upon the circulation of skilled people, material objects, and symbolic representations across distinct work settings, in such a way as to construct a continuous 'chain of practices' between the laboratory and the worlds of construction, academia, and design engineering. This analysis highlights the importance of the division of labour in shaping technical practice both inside and outside the laboratory.

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The Charles Lee Powell Structural Research Facility at the University of California, San Diego -- known as the Structures Lab to those familiar with it -- occupies two large, warehouse-like buildings near the centre of the campus.[1] The buildings sit across the street from one another, set back by expansive driveways which are used for storage and construction. Passing by the laboratory buildings, one's attention is immediately drawn to a forest of variously mangled concrete beams and columns which loom over the walls surrounding the driveways. Several similarly mangled columns have been set up in rows on either side of the pedestrian walkway approaching the laboratory, as strange monuments to what goes on within the laboratory. Large chunks of their surface concrete are missing, revealing the skeleton-like steel reinforcing bars within. In this Southern California setting, these ruined columns make a powerful statement, standing as tangible symbols of the fragility of the built environment in an area prone to earthquakes.

The symbolism is not accidental. The damage that has been done to these columns is meant to stand for, in a methodologically rigorous way, the damage which earthquakes may cause to California's transportation infrastructure. This sort of projection from the controlled world of the laboratory to the performance of technology in the field, it has been argued, is a central characteristic of all technological testing.[2] How this projection is accomplished is the subject of this paper.

Most of the research that goes on in the Structures Lab is related to earthquake engineering, the branch of structural engineering which deals with the effects of earthquakes on buildings, bridges, and similar structures. Structural elements are tested there, not to see if they can stand up to the static vertical forces imposed by gravity, but to see how they react to dynamic forces that act upon them in different directions, as in an earthquake. This field of research has become increasingly important, and increasingly well-funded, in the wake of the 1989 Loma Prieta earthquake in the San Francisco Bay Area and the 1994 Northridge earthquake near Los Angeles. In particular, the collapse of the Cypress freeway structure in Oakland during the Loma Prieta earthquake, and the consequent loss of life, spurred public fears about earthquakes and led the governor to appoint a board of inquiry. In 1990, the board issued a report which urged the California Department of Transportation (known as 'Caltrans') to immediately begin a program to retrofit all of the older freeway bridges in the state to current seismic safety standards.[3] This program was subsequently funded, at massive levels, both through legislative appropriation and through a voter-approved bond act. A portion of the funding was earmarked for research into the performance of existing bridges, possible retrofit techniques, and the improvement of design standards. Caltrans ended up contracting much of this work to the Structures Lab, along with a few other testing facilities. Early on in the process, one of the professors associated with the laboratory developed a method for strengthening reinforced concrete bridge columns by encasing them in steel jackets. This technique was subsequently validated by tests at the laboratory, and went on to become Caltrans' standard retrofitting method. Although the laboratory is involved in various other projects, most of the work that goes on there continues to be Caltrans-funded research on the performance of reinforced concrete bridge columns, and this is the area on which this paper focuses.

The Structures Lab sometimes looks more like a construction site than like a typical laboratory work setting. Most of the work being done there on a given day is related to the construction of large concrete test specimens (see Figure 1). These range from four meter tall column sections to full-scale columns of ten meters or more. On one occasion, a full scale model of a five-storey building section was tested inside the laboratory. While outside contractors are brought in to construct some of the largest test specimens, most of the construction work is done by the technicians and graduate students. They tie steel reinforcing bars into cages, build wooden forms, and pour concrete, all physically demanding tasks. Standard work clothing for everyone includes a hard-hat, concrete-spattered jeans, and steel-toed work boots. When testing finally begins, the instruments, cables, signal-conditioning cabinets and computer equipment which are more typical of laboratory research make an appearance, but they look somewhat out of place sitting on the dirty concrete test floor. This kind of juxtaposition is what prompted the laboratory manager to describe the Structures Lab as a 'construction environment that does scientific research'.[4]

Although substantial progress has been made toward understanding the distinct epistemological issues which testing can raise, the STS literature generally has not looked in detail at the material and organizational settings in which testing takes place. In the sociology of science, these aspects of experimental research have been addressed in detail in a number of laboratory studies.[5] By placing scientific experiments in the organizational contexts of specific laboratories, these studies demonstrate how the construction of scientific facts is grounded in the mundane, everyday work of laboratory personnel. Following this example, this study seeks to explain how testing, and the process of projection which it involves, is embodied in work practices in and around an engineering laboratory. The study of testing an a laboratory context highlights the importance of a particular aspect of laboratory work which has not been extensively studied: the division of labour among laboratory personnel.

As the preceding brief description of the laboratory indicates, testing there draws upon and is relevant to a wide range of social settings, from the world of construction work to design engineering to state transportation policy. Some have argued that projection is essentially a matter of establishing a similarity relationship between a test situation and the conditions a technology faces in actual use.[6] I argue, however, that projection should be understood as a process through which the local work practices of different social settings are tied together. Projection, in other words, is the mechanism through which the work practices of the test site are made to have an impact on the practices of engineering researchers, designers, policy makers, and others involved in technological production.

Testing and Projection

A good starting point for understanding what is significant about technological testing is the work of Donald MacKenzie and Trevor Pinch.[7] These authors, each writing generally within the SSK ('Sociology of Scientific Knowledge') tradition, make similar arguments based on the premise that 'all the issues that recent sociology of science has raised about <u>experiment</u> in science can be raised about <u>testing</u> in technology'.[8] In particular, they draw on the fundamental work of H.M. Collins on the replication of experiments.[9] Collins argues that an experiment, in itself, can never resolve a point of scientific contention because it is always possible, in principle, to challenge elements of experimental procedure. When an experiment produces a controversial result, it is generally possible for scientists to find fault with the experimenter or the methodology and dismiss the result as spurious. When an attempt is made to replicate an accepted experimental result, negative results can be explained away on similar grounds. In these disputes, judgments of similarity often play a crucial role: for example, important questions can arise about whether or not one experiment has been done under similar enough conditions to count as a legitimate replication of another.

Both Pinch and MacKenzie highlight a particular sort of similarity relationship that they find crucial in testing: that between the test situation and the actual working conditions of a technology. In order for a test to produce meaningful information about the performance of a technology in use, practitioners must believe that these two circumstances are similar in certain essential respects. Pinch calls this process of inference from test to use ‘projection’, and argues that it is the central issue that must be addressed in the sociological study of testing.

MacKenzie provides a detailed case study of the controversies surrounding nuclear missile testing, which shows how projection can become problematic when the similarity between test conditions and operating conditions is called into question. The tests he describes are meant to simulate, as closely as practically possible, the conditions a missile would face upon launch at the Soviet Union in time of war. In these tests, the warhead of a selected, operational nuclear missile is removed, and the missile is transported from its silo to a test range, where it is instrumented and then launched. In debates about whether to rely primarily on bombers or missiles, critics pointed out a number of ways in which these missile tests failed to accurately duplicate wartime conditions. For example, they claimed that the missiles themselves were given special treatment and maintenance prior to testing, and that there could be significant differences in the earth’s gravitational and magnetic fields on the test range and along a flight path towards the Soviet Union. In this way, the results of tests that may have seemed straightforward and credible to some were seen as invalid by others. From the perspective of the second group, a projection could not reasonably be made between a test and the performance of a missile in war.

This example, like others given by Pinch, presents a very convincing case that the credibility of testing depends upon social convention and judgments of similarity, but it also reveals a limitation of MacKenzie and Pinch’s approach. Although they aim to provide a general sociological account of testing, there is almost no consideration in their work of the practice of testing, or of the technical communities in which it takes place. Instead, their focus is on language and the representation of reality, as indicated by MacKenzie's claim that the product of '(socially) successful testing' is 'a credible statement of a certain form'.[10] Projection is depicted as a disembodied process of inference which bridges the gap between test and use. This reflects MacKenzie and Pinch's general concern with questions of knowledge and belief, which is in keeping with SSK's origins in a critique of positivist and rationalist approaches to the philosophy of science. The examples that they present tend to focus on the rhetorical construction and deconstruction of projection relationships in public contexts. While such examples are very useful for bringing out some of the characteristic epistemological features of testing, they do little to help us understand how testing fits into the practices of technical communities.[11]

Projection is Mediated and Embodied

MacKenzie and Pinch's work provides some important conceptual tools for understanding testing. In particular, the idea of projection seems to capture a fundamental property of testing. However, to describe this connection in terms of collective belief in a similarity relationship alone is to reduce technological practice to a set of disembodied ideas. Working with technology, even at the highest levels of design, depends upon certain kinds of skill that are not easily codified, and are not easily abstracted from the tools central to technological practice. So we should not expect that testing will generate only new technological <u>knowledge</u>, in the sense of abstract mental or linguistic constructs; we should also expect that it will generate new forms of technological <u>practice</u> – tacit knowledge, embodied skills, and other forms of working knowledge of technological artifacts. Projection, therefore, should not be seen only as the establishment of a similarity relationship, but rather as a process by which the practices of testing are more or less effectively linked to a wider context of technological practice. As I will explain in more detail below, this linkage is crucially dependent upon the movement of skilled people, material objects and symbolic representations across social settings.

The importance of embodied skill in scientific practice is convincingly demonstrated in the work of H.M. Collins on the replication of experiments, although this is an aspect of Collins' work which is not clearly addressed in MacKenzie and Pinch's work on testing. Collins studied the experimental replication of a new type of laser, the TEA laser, in various laboratories.[12] He found that successful replication depended largely upon unarticulated 'tacit' or 'skill-like' knowledge. This was reflected in the fact that research groups had difficulty making working lasers if they relied on written information alone. Generally, only those scientists who were able to maintain extended personal contact with personnel from other laboratories who had already produced a working laser were able to build their own. While such a strong dependence on personal contact might not be found in every case, Collins makes an important point: there is an aspect of experimental practice which is embodied, and not easily formalized. So it is not enough to analyze replication just in terms of similarity judgments; some description of the way people move between work sites is necessary as well.

Applying these considerations to projection introduces some new complexities. The replication of experiments generally involves establishing a common set of practices and artifacts across different laboratories. These laboratories may be geographically dispersed, but they are very similar social settings: they are organized around common goals, populated by comparable groups of people, and often make use of identical tools and instruments. The similarity judgments scientists make when comparing experiments generally presuppose this kind of cultural homogeneity. In contrast, projection involves making a connection between the practices of the test location and a larger world of technological practice, which may include social settings which are quite different from the test setting. These social settings may be organized around very different goals, be populated by different types of people, and involve quite different sets of practices and technologies. The missile tests which MacKenzie discusses, for example, may be carried out by specialized research staff on test ranges in the Pacific Ocean, but the results are taken up (or not) by missile designers, the nuclear strategy community both inside and outside the military, and by policy analysts and politicians who operate in a more public arena. Because these settings are differentiated specifically by the fact that they involve distinct sets of practices and distinct ways of relating to technology, projection, by definition, cannot be accomplished simply by establishing a common set of practices across different locations. Instead, for projection from test to use to be successful, some kind of translation or coordination has to take place between social settings which remain distinct.

The coordination of work across social settings is one of the central topics of the 'social worlds' perspective within interactionist sociology, which has also become an important school of thought within science studies.[13] This approach is a very useful starting point for analyzing projection. Anselm Strauss defines social worlds very simply as consisting of groups of people who participate in a common set of activities: for example, cancer research, mountain biking, or country music. This loose definition distinguishes social worlds from more narrowly drawn social categories, such as institutions or organizations. Identifying social worlds, however, can be a complicated process. Upon closer examination, they can usually be broken down into an almost infinite number of sub-worlds organized around particular subsets of activities. Strauss argues that a major analytical task in the study of social worlds is to look at the ways in which social worlds and subworlds intersect, and the various mechanisms which make such intersection possible.[14]

One way that these intersections can be managed is through 'marginal people' who are members of more than one social world.[15] Such people can help solve the problem of projection, because by virtue of their membership in adjacent social worlds, they may possess the skills and tacit knowledge of both. Because they understand the work practices of different worlds, they are in a unique position to help coordinate or translate work practices between sites. Also, by moving between social worlds, they may bring them closer together – for example, by bringing elements of the skill and knowledge of one world to the practices of another. Susan Leigh Star and James Griesemer have introduced an original variation on this idea. In the context of scientific research, they argue that marginal objects, as well as marginal people, can be used to connect different social worlds. These 'boundary objects' are 'those scientific objects which inhabit several intersecting social worlds … and satisfy the informational requirements of each of them'. They are 'both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites'.[16]

Projection can be understood, then, as a process in which the practices of intersecting social worlds or sub-worlds are linked through the movement of certain people and objects across the boundaries between them. This process creates a continuous chain of practices across social worlds. It is this chain of practices which makes it possible for test results to have an impact on the practices and ways of thinking of a wide range of social actors, both inside and outside of technical work.[17] In other words, it is a central feature of projection. Returning once again to MacKenzie's case study, we might be able to describe how test results are made available to missile designers through statistical analyses and test reports, or through the participation of designers in the testing process. The missiles themselves could be described as boundary objects between the test setting and the world of missile silo operations, carefully selected and transported to the test range so that the test launch can be considered (at least by some) to be just the same as a launch from a working silo. At the other end of the process, it might be that certain Congressional staff members with backgrounds in nuclear weapons policy play a crucial role in translating the technical details of missile performance into a form which is useful to members of Congress as they work to formulate positions in the public arena.

The stability of the projection relationship – that is, the strength of the chain of practices – may depend on a number of factors. For example, links between social worlds which involve more intense circulation of people and objects are likely to be stronger. In the hypothetical scenario presented above, the link between the social worlds of missile testing and missile design is likely to be particularly strong because actors from these worlds may work together and exchange information frequently. On the other hand, politicians and their staff members may have little interaction with missile testers or even designers, getting most of their information from written reports. Because of this lack of interaction, they may be more likely than designers to be sceptical of test results. But this need not be a universal tendency, particularly in cases where the testers might have a great deal of cultural authority.

Also, test results can more open to challenge the more complex the chain of practices becomes.[18] If a test is highly idealized, for example, and can only be projected to the performance of a technology in the field through a long chain of measurements, calibrations, and modelling techniques, there are many points at which critics could challenge the connection. But a very simple test, such as Pinch's example of saying 'testing … one, two, three … testing' to see if a microphone is working, may be difficult to dispute.[19] Of course, the simplicity or complexity of a chain of practices is itself dependent upon social convention, as when certain elements of a chain are 'black boxed' to the extent that they cease (at least temporarily) to be seen as sources of additional complexity.[20]

Approach of the Case Study

For this study of the Structures Lab, I describe a chain of practices that extends between a series of work settings, rather than distinct social worlds. Work settings, like social worlds, can be characterized by certain activities, by the particular sets of skills and artifacts employed in these activities, and by a common working relationship to technology on the part of participants.[21] However, work settings generally correspond to particular locations in which specific work tasks are carried out, rather than to a broader arena of activity. This unit of analysis is more appropriate for the detailed description of testing and engineering practice given here.

In the Structures Lab, there are four work settings which play a role in the testing and projection process (see Figure 2). The first setting is the laboratory itself, which is located within the two buildings described in the introduction. This is the setting where test specimens are built and the actual activity of testing takes place. This work is done by technicians, as well as by assorted graduate students and postdocs carrying out specific research projects. Next is the academic work setting, which is associated primarily with the graduate student and faculty office area, which is separate from the laboratory. Here, work revolves around planning tests, processing data using computers, writing papers and otherwise communicating with colleagues. Most of this work is done by graduate students under the supervision of faculty members. Finally, the design work setting is associated with Caltrans offices in Sacramento, the state capital. Here, engineers design new freeway structures, in part based on information gained through testing. Academic researchers occasionally appear in this setting as consultants or design reviewers.

Besides these three discrete work settings, work in the laboratory setting is based on the practices of some work settings which are so widely distributed that they could almost be considered social worlds in themselves. The most prominent of these is the construction industry. Technicians hired from this setting bring to the laboratory skills in carpentry and steel and concrete work which are necessary for the construction of test specimens. Other technicians bring in expertise gained through outside work in a variety of other areas, such as electronics and hydraulics.

The relationship between work settings and the human, material, and symbolic intermediaries which connect them can be a complicated one. In one sense, work settings are like social sub-worlds, organized around a particular set of activities, but in other ways they are more like zones of intersection between social worlds. Laboratories are a good example. On the one hand, they are their own little social worlds, populated by various groups of people working around a common goal. On the other hand, the different groups of people involved in laboratory work can themselves be considered part of distinct social sub-worlds. Scientists, for example, may see their laboratory work as continuous with a set of related activities, like attending conferences and writing papers for publication. Some technicians, however, participate only in laboratory work, but may be involved with aspects of this work that scientists do not or cannot participate in. Each group is likely, as well, to make use of distinct sets of technological artifacts. In the laboratory, these social worlds intersect.

The role of work settings as intersections between social sub-worlds makes them similar to what Peter Galison has called ‘trading zones’: locations in which members of divergent social groups are able to successfully interact while maintaining distinct cultural identities.[22] Because of this characteristic, the work settings described here are connected to one another in a subtly different way than social worlds. Although social worlds are connected primarily through marginal people and marginal objects, this is not necessarily the case with work settings. Work settings are much smaller units than social worlds, so it is much easier for a given actor to be a participant in more than one work setting; in fact, most actors will participate in more than one. Work settings are therefore connected through a generalized division of labour and circulation of technology, not just through certain marginal people and objects..

Goals of the Case Study

In addition to its usefulness for illustrating a new conception of projection as a chain of practices, this case study extends current work in two other ways. First, as a case study in testing, it focuses on testing primarily in the context of an ongoing process of research. Most of the existing case study literature on testing focuses on what some engineers call 'proof tests'.[23] A proof test is designed to test a complete technological system under conditions as close as possible to those it would experience in use, in order to make a projection about whether it will work as it is supposed to.[24] The nuclear missile testing described by MacKenzie is a particularly clear-cut example of this kind of test.[25]

The testing done at the Structures Lab, by contrast, plays a much more ambiguous role. While some tests are done to determine whether a particular design will work in the field, many others are at least partly oriented towards gaining a better understanding of the fundamental behaviour of building materials like reinforced concrete. These tests have some of the characteristics of experiment, in that they are oriented towards gaining new basic knowledge, rather than just proof of functionality.[26] One result of this is that there is more of an emphasis on replicability than may be found in some test situations, even though, on the whole, projection is a more important problem to these researchers. Also, an analysis of testing in terms of similarity relationships becomes less convincing for this kind of testing, because maintaining the similarity between test objects and objects in the field is often secondary to other methodological concerns. This sort of testing makes a particularly good case study precisely because the similarity between test and use is full of ambiguity, yet projection seems to occur anyhow. If testing is to be understood at the most general level, it is important to look carefully at this kind of research-oriented testing.

This case study also aims to make a contribution in the area of laboratory studies. While many ethnographic studies of scientific laboratories have been oriented towards understanding the work routines of scientific research, very few actually discuss the distinct roles that faculty, technicians, and students play in the division of labour in the laboratory, even if their work practices are described in great detail.[27] The Structures Lab is a particularly good location for addressing this issue. In part, this is because it is a fairly large laboratory with a somewhat hierarchical organization. But also, because it is a testing laboratory run by engineers, work there is connected to diverse bodies of practice which have origins well outside the immediate research community. It is difficult for any one individual to understand or be competent in all of these areas, which leads to a more extensive division of labour. Technicians, graduate students, and faculty members all play quite distinct roles in research at this laboratory.

The division of labour in the laboratory has not been entirely ignored, however. The most significant discussion of this issue can be found in the growing literature on technicians. Steven Shapin, for example, sifts through the historical record to reconstruct the role of ‘invisible technicians' in 17th century English science.[28] Chandra Mukerji similarly discusses the role of technicians in 20th century oceanography.[29] Both note that technicians' work seems to be devalued because of its routine, manual character and association with machinery. The work they do is often viewed, in the end, as a mere extension of the will of the scientists they work for.

The precise nature of the division of labour between technicians and scientists is discussed in more detail in the work of Stephen Barley.[30] Barley and a group of collaborators conducted a comparative study of technicians in a variety of fields, ranging from laboratory technicians to emergency medical technicians. This study found that technicians' work, in whatever field, generally occurred at an 'empirical interface' where the material world is manipulated to produce symbolic representations.[31] In their role as mediators between these two realms, technicians fit into the division of labour in two distinct ways. Some technicians, like those who fix computer problems, serve as 'brokers'.[32] They are responsible for taking care of the technological systems that others use to do their work. The people they serve often have little knowledge of the technology in question, and as a consequence generally inhabit a different social world from the technicians, according to Barley. These technicians generate symbolic representations primarily for use in their own work. Other technicians serve as 'buffers' between professionals and the material world.[33] Their job, essentially, is to ensure that there is a reliable correspondence between the material world and the symbolic representations that they produce, so that professionals can use these representations to add to their own knowledge. Laboratory technicians are a paradigmatic example of this type. Barley notes that technicians in this role generally share a social world with the professionals they work for, and are able to discuss problems in a common language. In a pinch, the professionals might even be able to take over some of the work of technicians, although they might not do it well.

Although the technicians in the Structures Lab do appear, in some respects, to work at a boundary between material and symbolic worlds, they are not alone in this respect. Each of the different groups of actors at the laboratory – faculty, graduate students, and technicians – serves, in some substantial aspect of their work, as an intermediary between the material and the symbolic. Also, an 'empirical interface' can generally be more fully described as an interface between work settings. Human beings never enter into unmediated confrontations with the material world. These interactions are always shaped by traditions of practice and skill. The empirical interface at which technicians work, for example, is more importantly an interface between a body of practices dominated by highly skilled manual work and a body of scientific practices dominated by the manipulation of symbols. So while the concepts of 'buffer' and 'broker' can help explain the texture of work at the Structures Lab, they do so within a broader framework in which each actor serves as an intermediary between distinct work settings, making it possible to establish a continuous chain of practices between settings. It is the need for this kind of mediation that shapes the division of labour in the laboratory setting.

A Tradition of Testability: The Quasi-Static Method

Before I move on to discuss the specifics of the chain of practices at the Structures Lab, it is important to understand the basic principles of the testing method used at the laboratory. In earthquake engineering research, what might be called a 'tradition of technological testability' has developed.[34] There are several widely used methods of laboratory testing in the field.[35] Most of the tests done at the Structures Lab are of the 'quasi-static' variety. Purely static testing, which is rarely used in this sort of research, simply involves subjecting a test specimen to a constant level of force or weight. Quasi-static testing, on the other hand, attempts to replicate the side-to-side shaking of an earthquake, although in a simplified form and at a very slow speed.[36] Another common method is 'shake table' testing, which attempts to simulate the dynamic motions of an earthquake in real time, using a hydraulically-driven table.[37]

Both quasi-static and shake table testing have advantages and disadvantages. While shake table testing simulates the motions of an earthquake in a very sophisticated way, most shake tables can only accommodate relatively small-scale models of structures, and the tests go by so quickly that it is difficult to obtain certain kinds of data from them.[38] Quasi-static testing, however, simulates certain key aspects of the effects of earthquakes on structures, but uses less complicated equipment and is done at a slower speed which facilitates data collection. For these and other reasons, quasi-static testing has become the dominant form of laboratory testing in earthquake engineering: one source estimates that 85 to 90% of all published experimental research in the field is based on this method.[39]

One of the most important long-term research projects being done for Caltrans is directed towards studying the behaviour of reinforced concrete bridge columns of the sort which support freeway overpasses. A given series of tests generally proceeds through a process of parameter variation. For example, the main focus of my participant observation in the laboratory was a series of tests being done on flared columns.[40] This series included tests of models representing an older column design with flares, the same design with the flares removed, and the same design again with the flares partially cut away as a retrofit measure; it then moved on to newer-style Caltrans columns, including one without flares, one with flares, and one with the flares partially cut away.

Column tests are typically done on 40% scale models, although some full-scale tests have been done as well. The Structures Lab, like many other laboratories that do this kind of testing, is built with a massively reinforced and prestressed concrete wall and floor, often called a 'reaction wall' and 'strong floor'. The columns are tested in an inverted position (see Figure 3). The bottom of the test specimen (which would be the top of an actual column) is bolted down to the floor, and a large hydraulic actuator -- about fifteen feet long when extended -- is bolted to the wall and to the top of the specimen. This actuator is hooked up to a computer control system which can precisely control the forces and displacements which are applied to the test specimen. The steel reinforcing bars inside the column are outfitted with hundreds of strain gauges which will measure the deformation of the steel during the test; these are complemented by other externally attached instruments that measure column curvature, top displacement, and base slippage.

Tests begin slowly, with very small displacements well within the "elastic" range of behaviour of reinforced concrete. Elastic displacements are those which do not permanently deform the concrete and steel. The displacements increase in a series of steps, with three back-and-forth cycles generally performed at each level. As the cycles continue, they soon move past the point of "first yield," when the steel reinforcing bar ('rebar') begins to deform permanently, and into the area of inelastic behaviour. The test continues to progress, cycling to ever larger displacements. The concrete begins to fall off in chunks after a while, exposing the rebar, which at this point is still able to hold the interior concrete together. As the test nears its end, the bars begin to snap, with loud booms. Now the concrete begins to lose its integrity completely, which marks the end of the test. This whole process is quite slow, involving in the neighborhood of twenty back-and-forth cycles over as long as an eight-hour period. Most of the time is actually taken up in pauses between cycles, during which the students and technicians who are conducting the test carefully look over the specimen, mark any surface cracks with felt-tipped pens, and photograph the resulting patterns. By the end of the test, the column is covered with a network of marked cracks which radiate outward from the areas where the concrete has disintegrated. These photographs, along with the numerical data from instruments, make up the data which are taken away for further analysis.

The Case Study: Three Intersections

In this case study, I focus not on specific work settings or bodies of practice, but rather on the interfaces between them. By examining how objects, representations, and actors move across these interfaces, it will become clearer how the practices of one setting can have an impact on the practices of another, even as the settings themselves remain distinct in certain ways. At each of these intersections, establishing a relevant similarity relationship is in some way problematic. Instead of focusing on this problem, therefore, much of the work at the interfaces between work settings is devoted to finding creative ways to manage ambiguity where there are no clear similarity relationships. In each case – for example, in making the connections between test specimens and structures in the field, test results and the performance of structures in earthquakes, or the practices of researchers and designers – we find that actors have organized boundary objects and boundary-crossing people to ensure that relevant connections are made between the practices of different work settings despite these ambiguities.

Outside Practices and the Laboratory

The point at which the laboratory work setting connects with outside work practices and technologies is a particularly crucial location, because it is through this intersection that most of the 'raw materials' of research make their way into the laboratory. This includes many of the skills that are necessary to laboratory work. The crucial problem faced by researchers at this intersection is that of bringing the technology to be tested into the laboratory in a form that is amenable to the demands of research, yet still able to reasonably 'stand for' the technological infrastructure outside of the laboratory. To this end, an ensemble of 'hybrid objects' – in the form of test specimens – and skilled technicians is deployed.

Test Specimens

A key feature of the specimens tested in the laboratory is their commonality with structures found outside of the laboratory. Indeed, in some cases the test specimens are meant to represent specific, existing freeway structures. But in order to be useful to research purposes, test specimens have to satisfy a number of conflicting demands. As a result, researchers find it necessary to have these models built on-site, so that they can be built in a way which reconciles some of these conflicting demands. There are a number of ways in which test specimens differ from their counterparts outside the laboratory. At the most straightforward level, they differ because a great number of measuring devices have to be incorporated into their construction. But this issue aside, test specimens are also constructed and sometimes designed differently to meet specific research needs.

The main difference in the construction of test specimens and the construction of structures in the field is a matter of precision. One of the laboratory technicians, a former construction worker, explained:

> You have to do it here [with] more precision than you would on the outside, because this is a test, everything has to be set, the steel has to be just set at a certain spacing, where if

> the steel is off an inch or so it doesn't make any difference in the real world, you're not in a test. And when you start to test something, everything should be just as drawn. You can't slide a bar a couple of inches and get away with it, you know, because that's not going to give you the exact reading that they want.[41]

The point here is not that the construction industry has low quality standards, but that most structures are designed with enough redundancy that minor deviations in the placement of reinforcing steel will not compromise their integrity.[42] In the test situation, however, the goal is to determine precisely how a structure fails, so researchers want to know the physical dimensions of the test specimens to a high degree of accuracy. Also, as one of the professors pointed out, structural tests are not done in great enough numbers to be able to simulate the actual range of variation in construction in a statistically rigorous way. Instead, researchers prefer specimens to be built precisely enough that test results can be used as a reliable basis for developing computer models. These computer models can then be used to simulate the actual variability of structures, if this is deemed necessary.[43]

While all test specimens are built according to these higher standards of precision, some specimens are actually designed differently than anything that exists in the field, in order to highlight certain aspects of structural performance. One of the engineering professors gave an example:

> [If] we want to be close to a balance point between two different failure modes, flexural failure and shear failure mode, for example … we design the test specimen to be right

> close to that balance point so we can examine that critical area. If we were designing real structures, we'll design to be away from that area.[44]

This is a typical case in which the need to understand a fundamental aspect of the behaviour of reinforced concrete takes precedence over the need to make the test specimen as similar as possible to artifacts outside the laboratory.

The test specimens, then, are a particular kind of boundary object. Some objects can cross boundaries easily because they are flexible enough to be adapted to a variety of local circumstances. These test specimens, however, are built as hybrid objects which incorporate elements relevant to two quite different work settings. In these objects, the concrete and steel of real infrastructure meet the electronic measuring devices and epistemological demands of science. Objects like these do not have to move in order to cross boundaries; their existence implies a prior boundary-crossing movement on the part of those who build them. It is the laboratory technicians who make this transition.

Technicians

As the laboratory has expanded, an initially very simple division of labour has grown increasingly complex. Technicians who were hired early in the history of the lab – in the mid-1980s – tend to have experience and skills in more than one area. One of these technicians, for example, worked in oceanography for fourteen years as a shipboard electronics technician, then ran his own concrete business for several years before coming to work at the laboratory. But it proved difficult to find people with this range of skills, and as the laboratory grew, a new hiring strategy emerged. Instead of seeking individuals who could do many things, the laboratory began to hire technicians with specialized skills in two distinct areas: construction, and electronics and hydraulics.

Electronics and hydraulics technicians are generally responsible for test setup and instrumentation, and for the maintenance of instruments and testing equipment. These technicians often have very diverse backgrounds, because their work revolves around an array of machinery which is fairly particular to the laboratory. For example, one of these technicians had an undergraduate degree in bioengineering, worked for several years as a theatrical lighting technician, and then worked for a while as a general support technician for the mechanical engineering department before being hired by the laboratory.[45] The head technician in this category is unique in having a Ph.D. in structural engineering, acquired through graduate work at the laboratory.[46]

Here, I focus mainly on the work of construction technicians. These technicians are primarily responsible for the actual construction of test specimens, as well as for operating heavy machinery like cranes and forklifts, and typically have extensive experience in the construction industry. One of the most valued construction technicians was hired by the laboratory after working in the construction industry around southern California for over forty years. He was perceived by researchers as being especially well suited for laboratory work because of his extremely perfectionist attitude.[47] The laboratory is crucially dependent upon technicians like these, because of the need to construct specimens for testing purposes which incorporate features of construction in the field. These technicians bring skills in steel work, carpentry, and concrete pouring which professors and graduate students usually do not possess to any great degree.

Many of the construction technicians working at the laboratory are at or near retirement age. Researchers value these older workers because of their greater skill, but laboratory work is also attractive to these workers because it is quite a lot less strenuous than construction work in the field. It also pays considerably less, which may drive away younger workers. The technician mentioned in the previous paragraph compared the physical demands of the two types of work:

> You're doing it here on a much smaller scale, and the heavy work is done by my friend, the crane, instead of my back. A lot of things that you do out on a bridge, well, you can't reach with a crane, or they only give you X number of hours to finish the job, and you better have all that heavy work done, or otherwise you have to find another way of doing it. Most of the time it's with the muscles in your body.[48]

Many of the construction technicians are also drawn to laboratory work because they find the research environment interesting. One technician described his lifetime strategy in the construction business, which carried over into his interest in laboratory work: 'when I see something being built, [a] new type structure ... or a new way of doing it, I try to get on and learn how'.[49] Another technician explained that 'the part I really like about it [is] every day you learn something ...you get to learn things that you wouldn't when you build something out in the field'.[50] Part of the reason for this is that the laboratory brings engineers and construction workers together in a way that rarely happens in the field, as this technician described:

> People building whatever out in the field, houses or bridges or whatever, they're always saying look at this, look at the engineers and architects, this is stupid, why did they do this? ... And a lot of it is, [the engineers and architects] don't understand how things go together when they draw the drawings, and they'll draw things that can't work. ... but a lot

> of times they have a reason that doesn't make sense to you out in the field, and now, after being here [in the laboratory] for a while, you can see a lot of times that there is a reason, some of the things that appeared stupid before.[51]

This statement reflects the important intermediary role that these technicians take on in the laboratory. If their work were limited to building and moving test specimens, they would fit the 'broker' role described by Barley, since they are taking care of the physical infrastructure of laboratory work. But their work is not limited in this way. Construction technicians also play a more active role in shaping laboratory practices. In particular, they interact extensively with graduate students in the laboratory, and play a major role in training them for laboratory work. Partly, this involves teaching graduate students some of the skills and 'tricks of the trade' that they need to assist in the construction process. For example, on one occasion I worked with a graduate student who was trying to assemble wooden forms around an assembled 'cage' of steel reinforcing bars, prior to pouring the concrete. The column was to have about a dozen steel bars protruding from it to serve as instrument attachments, and the wooden forms had holes drilled in them to fit over these bars. However, the student had a great deal of trouble maneuvering the large plywood forms so that the holes and bars all lined up at once. He consulted one of the construction technicians, who told him to fit lengths of metal pipe into the holes, then slide the pipes over the ends of the bars before finally positioning the forms. This solved the problem. Besides this sort of troubleshooting, it is the technicians who usually instruct students in basic construction techniques and in the use of machinery.

Through experiences like this, technicians and students start to share a common social world, which begins to make the technicians' role more like that of a 'buffer' between work settings. Technicians also act like buffers because they do play an active role in translating between the worlds of material and symbolic practice. They do this mainly through working with students on design drawings. Being able to produce design drawings which can be successfully translated into built structures is one of the most important aspects of laboratory work, just as it is in structural design. Interpreting these drawings, whether in the laboratory or in the field, almost always involves some degree of interaction between engineers and builders. In the Structures Lab, the problem is aggravated by the fact that some graduate students do not have a great deal of practical design experience. When they are working on a specimen with a new design, graduate students frequently consult with technicians to make sure their design drawings are in accordance with standard construction practice. A technician described how this process worked with one inexperienced student:

> [He] didn't quite know how to set things up, I mean ... his drawings suffered a little bit, so you have to make some interpretations to make it work. ... I'd say to him, we can't do it this way, we have to do it this way, and he would change the drawings and make it all work.[52]

Through interactions like these, construction technicians help ensure, in one important respect, that there is a reliable connection between symbolic representations used by the engineers and the material objects in the laboratory. They do so as part of their larger role of bringing the work practices of the construction industry into the laboratory setting.

Construction technicians and test specimens relate to each other in rather complex ways as they bridge the gap between work settings. At one level, technicians play a key role in the construction of test specimens, which themselves serve as hybrid boundary objects. But in so doing, they also come to serve an important role by making certain skills and practices available to everyone who works in the laboratory, in the role of teachers and advisors. The test specimens, in this case, play their mediating role only with the close support of skilled human beings. At the same time, however, as common objects of work they play a pivotal role in the transfer of knowledge and skills between technicians and graduate students.

The Laboratory and Academia

There are two central problems that researchers face in making the work done in the laboratory relevant to the broader academic field of earthquake engineering. The first problem is how to organize testing methodology and computer modelling techniques in such a way that test results are made relevant to the entire field, which is after all interested mainly in the behaviour of the built environment outside the laboratory, not test specimens in the laboratory. The second problem is a somewhat narrower subset of the first: how to make sure that the data which is taken from the laboratory to the academic offices for further processing is, in fact, an accurate representation of the performance of the specimen during the test. In part, this is done through an process of independent calibration and testing of components of the test setup. Even with this calibration, however, researchers feel that ability to interpret data is somehow enhanced by direct experience of the testing process, and for this reason graduate students are required to take a major role in both producing and interpreting data.

Test Methodology

Earthquake engineering researchers think that quasi-static tests produce results that are similar to the effects of an actual earthquake on a structure, but only at a fairly general level, as one researcher explained:

> We believe that if you take a structure through three complete cycles at the maximum level of displacement, that's more severe than would ever happen in an earthquake in which that displacement was the maximum ... by definition you're only going to have one cycle or one half cycle to the maximum displacement [in an earthquake] ... so by doing three cycles plus and minus to that level, you're pretty conservative in terms of the response.[53]

But researchers are not satisfied with this very general similarity relationship; they want to be able to use test results to accurately predict the behaviour of specific structures in real earthquakes. Here they face a dilemma: for various methodological reasons, explained below, both the test specimens and the test method are highly idealized, making them manifestly different from any particular structure or earthquake. This makes it difficult for researchers to see a direct correspondence between any particular test and the performance of a structure in an actual earthquake. As a result, when researchers explain this correlation, they do not usually talk about direct similarity relationships, but about intermediary devices that serve to connect the two domains. The most important of these devices are computer programs which enable researchers to model the behaviour of any given structure. In conjunction with the test methodology described here, these models play an important role in rendering the practices of the laboratory useful to academic researchers.

The quasi-static testing method itself is designed to mimic the forces of an earthquake only in a very general way. Unlike shake table tests, quasi-static tests put a structure through a very regular, predetermined sequence of steadily increasing displacements which is not believed by researchers to directly imitate the effects of an earthquake. Although one of the reasons that this method is used at the laboratory is because it is simpler and less labour-intensive than shake-table testing, this choice is not just a practical trade-off. In fact, quasi-static testing is felt to provide certain advantages in terms of the overall usefulness and applicability of test results.

One such advantage is that it standardizes test results, and therefore makes tests easier to replicate. One researcher described why this is important for the generation of knowledge in the field:

> Doing standardized testing is rather important if you're going to be able to compare one test to another, and one laboratory to another, so if you put a particular structure through one earthquake record, and somebody else does another structure through another earthquake record, you really can't compare them. But if we both work to a standardized testing pattern, which simulates or represents the response in earthquakes, then you can at least compare ... and increase the database.[54]

But it is not just concerns about standardization that make quasi-static testing useful. The idealized character of the method is also felt to make the test results applicable to a wider range of actual earthquake conditions. As one researcher described it,

> You have to make it so it doesn't really have the characteristics of an individual earthquake, because you don't know what the characteristics of the earthquake that's going to hit the structure will be, you have no means for really being able to tell that. So what you try and do is something or other that has generic characteristics of relatively increasing earthquakes.[55]

In this case, drawing a tight, one-to-one comparison between a test and a particular earthquake is not seen as a methodological advantage; in fact, it is seen as a disadvantage because the precise nature of an earthquake that is likely to hit a particular structure cannot be easily predicted, given the present state of knowledge about earthquakes. Because of this uncertainty, it is felt that simulating earthquakes in a very general way provides a better connection between the tests and the performance of actual structures than could be achieved through more direct methods.

Computer Models

This reliance on a very generalized testing method, however, creates a new set of problems. Now, in order to get the kind of precise, quantitative correlation that researchers want between tests and the performance of structures in actual earthquakes, an intermediate step is required: computer modelling. According to researchers at the Structures Lab, the primary purpose of the testing they do is to confirm, or calibrate, these models.[56] These analytical models, which are usually realized on computers, can then be used to more accurately simulate the effects of a specific earthquake on specific structures. Almost all the research done at the laboratory involves either the generation of new modelling tools, or the modification and refinement of existing tools to cover a broader range of cases or to be more accurate. This is consistent with trends in the entire field of structural engineering, where computer models are routinely used in design work; indeed, they have become so prevalent that there are now engineering firms which focus almost exclusively on the development and application of these models. At the Structures Lab, most of the actual work of developing models is done by graduate students.

There are a variety of modelling techniques in current use in earthquake engineering. One example is 'finite element' analysis, which essentially breaks a structure down into small pieces, each of which can be modeled fairly simply. Models can be either linear -- that is, modelling only the elastic behaviour of structures -- or nonlinear, in which case they attempt to simulate effects such as the deformation of steel and the cracking of concrete. In order to simulate the dynamic response of structures to earthquakes, techniques of 'time-history analysis' are often used. This method can be used to simulate the response of a whole structure to specific ground movements. Test results are used to help refine the assumptions built in to these models about the nonlinear behaviour of materials and about the interactions between materials, such as the degree of slippage between concrete and steel.

Researchers feel that this process of calibration between tests and models has led, over time, to very good correlation between models and test results:

> Our computer models enable us to predict the force-displacement response, and we typically do that before the test, we plot it on to the paper that is going to be used for automatically plotting the x-y response [of the test specimen] so we can compare a true prediction of response and what we actually get, and we typically get excellent agreement of the whole curve now. Now this is something or other which we couldn't get ten years

> ago. ... We really believe we have very good models, just because of the fact that we see the agreement between theory and experiment.[57]

However, this correlation between tests and analytical models is not always perfect, particularly in situations where the structural element being modeled has an unusual design or complex shape. For example, on one occasion a bridge pile was tested in the laboratory which had an unusual design: a pre-stressed, cylindrical shell made of high-strength concrete, surrounding a reinforced core of normal concrete. Two independent computer models each failed to predict certain aspects of the pile's behaviour under stress. After the test was completed, the models were refined so that they could accurately duplicate the performance of the pile. In such cases, the hope is that the refined models will be able to predict the outcome of future tests.

Although the close correlation between test results and computer simulations has made earthquake engineering researchers very confident in their ability to project between the two, they do not have quite the same degree of confidence about connecting these models to the performance of actual structures in earthquakes. Data on the effects of earthquakes on structures come mainly from field observations of earthquake damage. After a major earthquake in any built-up area, earthquake engineers from research groups all over the world try to get into the area as quickly as possible in order to take pictures of the damage before it is cleaned up. While it is usually only faculty members who are able to make international trips, a team of faculty and students from the laboratory visited and photographed all of the sites of major damage to bridges in the Northridge earthquake within hours of the event.

The data that can be gathered about the effects of earthquakes through these investigations are largely qualitative observations about the nature of the damage. This can be supplemented by seismographic readings giving a general idea of the forces to which a given structure might have been subjected. Analytical models can then be used along with these data to try to generate probable failure scenarios. After the Northridge earthquake, faculty and graduate students from the Structures Lab put together a report which analyzed a number of structural failures in this way.[58] Such exercises give researchers some measure of confidence that their analytical models can be applied to real-world situations, but they usually do not produce the kind of tight correlation that researchers believe exists between analytical models and test results.

The uncertainty of this connection is reflected in the fact that earthquakes still quite frequently present researchers with unanticipated effects. As a result, each new earthquake in a built-up area is seen as an important learning experience. One of the researchers explained:

> We are by no means at the stage where we can say look, we know everything about it. Events like this help by pushing the state of the art, it’s like a turbocharge ... every time you have an earthquake then research jumps again a couple of steps, but we still need to do a lot of work there.[59]

Data

The production of the data that goes into computer models poses some significant problems in itself. The most significant data obtained from a test come from the numerical readouts of the many gauges and measuring devices which are attached to, or built into, the test specimen. Throughout a test, readings from these instruments are digitally recorded every few seconds. These readings are recorded by a computer system, and then saved on floppy disks for further processing on computers in the office area. The most commonly used representation of test results is a plot of the force applied to the column by the hydraulic actuator versus the displacement of the top of the column, called a ‘hysteresis’ graph (see Figure 4). Good results can be seen fairly easily on such a graph. Very generally, if the loops on the graph become large and rounded, this shows that the specimen is able to absorb the energy of an earthquake while retaining its ductility, or ability to resist repeated deformations. More vertical, compressed loops, however, reflect a lack of ability to absorb energy and lower ductility, which can make a structure more likely to fail in an earthquake. These graphs can be compared to predictions of force-displacement response in order to test analytical models, as shown in Figure 4.

Researchers try to ensure that the data used to produce these graphs, as well as higher-level analytical results, are accurate through a variety of checks, tests, and calibrations. Strain gauges, for example, convert variations in strain into variations in voltage. Prior to a test, each data channel to which a gauge is connected has to be carefully calibrated so that a given voltage reading corresponds to the same strain in every case. Also, readings from different instruments can serve as a check on one another. For example, while the main sources of data from the test are strain gauges and devices for measuring the displacement and force on the top of the column, there are also instruments that measure the angle of the column, its curvature, and the displacement of the bottom of the column. The readings provided by these instruments are somewhat redundant, but if a problem arises, they are sometimes used to verify the accuracy of other instruments.

The readings of the instruments themselves, however, cannot be accurately interpreted if the basic properties of the test specimen -- particularly, the strengths of the materials -- are not known. Steel is manufactured so reliably that its strength can usually be determined with sufficient accuracy just from data provided by the manufacturer. But concrete is a material which can vary drastically in strength depending on its moisture content and the amount and nature of the aggregate it contains. When the concrete is poured for the specimen, therefore, it is carefully mixed to contain exactly the proportions called for in the design. One way this is measured is through a ‘slump test’, in which a sample of concrete is packed into a specially-designed cone which is upended on the ground; the distance the wet concrete sinks as it spreads out is then measured. The test is repeated until the mixture is exactly right.

Still, it is understood that the concrete will exhibit a certain variability even if its composition is carefully adjusted during construction. To account for this variability, samples of concrete are taken at several points during the concrete pouring process. These samples are packed into foot-long plastic cylinders with lids that are carefully labelled with the source of the concrete. The cylinders are then placed in storage to cure. Then, on the day that the specimen is tested, they are removed from storage and their strength is measured using a standard materials testing machine. This parallel testing process enables researchers to calibrate their test results in relation to the independently measured strength of the concrete.

All of these checks and calibrations are oriented towards the problem of metrology. That is, how to ensure that a measurement made in one place and time can be accurately compared to a measurement made elsewhere: for example, in a different part of the specimen, at a different point in the progress of a test, or in a different test or a different laboratory altogether.[60] As we have seen, the ability to compare test results is crucial if researchers are to be able to use test results, in aggregate form, as a basis for the development of analytical techniques and computer models.

Graduate Students

The key actors in the mediation between the laboratory setting and the academic world are graduate students. While technicians work almost exclusively in the laboratory, and faculty members spend most of their time in the offices, graduate students routinely move between the two settings. After taking classes for a year or two, most graduate students begin a laboratory research project which will be the basis for their dissertation. One professor explained that graduate students function as ‘project managers’. While faculty members are responsible for carrying out the overall research program, each specific series of tests is delegated to a graduate student.[61] The students supervise these projects from beginning to end: they design the test specimens, make drawings, and consult with technicians on matters of construction; they make sure that all the necessary materials are available; and they do a great deal of the construction, instrumentation, and test preparation themselves, with substantial help from technicians. They also oversee the testing process itself and the collection of data, and do most of the analysis, computer modelling, and writing of papers and reports.

Graduate students are given such a wide range of responsibilities intentionally. This professor explained that graduate students at some other structural engineering laboratories are responsible mainly for designing tests and processing data, relying on technicians to do most of the actual work in the laboratory. He argued that it is much better to involve students in the whole process, for two reasons. First, the process is made faster and more efficient, since the graduate students and technicians are able to coordinate their work much more effectively. Second, graduate students end up with a better understanding of the whole testing process, which he believes is reflected in the higher quality of the papers and reports they produce.[62] Although they did not mention graduate students specifically, Caltrans engineers generally did agree that reports produced by the Structures Lab were more immediately useful than those produced by other laboratories.

Although they are usually well-prepared for the analytical side of their work by the classes they have taken, laboratory work is often quite a learning experience for graduate students. Some students come to graduate school with previous experience in engineering practice. A typical example was one student had worked for a bridge contractor as a field engineer on construction projects during college.[63] Such students are generally well-prepared to take on the 'project manager' role. Others seem to find the transition from classroom to laboratory more difficult. Students also have varying degrees of experience in the use of common tools. Even those with a great deal of general experience usually do not know much about the tools and techniques of steel and concrete work. As I have described previously, it is the technicians who take the lead role in socializing graduate students into these aspects of laboratory practice. Despite the challenge, however, it is the rare student who is unable to learn enough relevant skills to be useful in the laboratory.

In the broader division of labour at the Structures Lab, it is the graduate students, rather than the technicians, who emerge as the primary 'buffers' between the materiality of laboratory work and the symbolic products which make this work relevant to the academic and design communities. They play a slightly different role than the technicians described by Barley, however, because they are less fully immersed in the world of the laboratory, and are responsible for manipulating the symbolic data as well as producing them.

While graduate students may not take on such an intermediary role in every laboratory, it is no accident that they do so at the Structures Lab. Researchers there appear to be specifically dissatisfied with the traditional division of labour between laboratory technicians and researchers, in which the technicians simply supply the data and maintain the material infrastructure which scientists use for their work. Instead, they seem to believe that it is important that some of the tacit knowledge gained through laboratory work travel with the data, and that such knowledge is important for its correct interpretation. In particular, researchers who understand the circumstances of production of the formalized knowledge they generate may be better able to give advice to designers, especially if the designers need to apply this knowledge under circumstances not anticipated by laboratory testing. This is a role in which graduate students may often find themselves when they become faculty members.

Academia and Design Engineering

Although many aspects of research at the Structures Lab are oriented towards producing results which will contribute to the development of a body of academic knowledge, most people in the field would agree that the ultimate purpose of earthquake engineering research is to develop techniques which can be applied to practical design problems. Perhaps more importantly, much of the funding for research in this field comes from organizations like Caltrans, whose main interest does not lie in supporting basic research. However, academic researchers and design engineers do work in different settings, and sometimes see engineering problems very differently. Because of this, a certain amount of translation has to take place in order for research results to have an impact on the practices of designers. One way this is done is through the movement of texts and computer models from the academic to the design setting. These sources are sometimes aggressively reinterpreted and modified in the process. A certain degree of continuity in interpretation is maintained, however, through personal interactions and negotiations between researchers and designers.

Texts and Computer Models

Besides their role in academic research, computer models serve, to a limited extent, as links between the academic and design settings. Some computer models developed in the academic setting have, over time, made their way into general use in organizations like Caltrans, although typically they are modified extensively by designers.[64] More commonly, it appears that engineers who develop computer models for industry and government learn general techniques of modelling from academic research., which they then use to build their own models.

Most Caltrans engineers, however, seem to be influenced more directly by written sources. These take several forms. Reports from the Structures Lab on specific test series provide exhaustively detailed information about methodology, the construction of test specimens, data collection, and test results. They also include interpretations of the results and suggestions about changes that could be made in design practices. In addition, researchers at the laboratory occasionally write reports for Caltrans on more general design issues, such as retrofit techniques for bridge columns.[65] Laboratory researchers have also produced a textbook which is used as a reference by many Caltrans engineers.[66] Many of these written documents are distributed widely within Caltrans, and their suggestions are often incorporated into design practice either in the writing of new codes, or through their impact on the methods of individual designers who read them.

The design tools and recommendations in these documents, however, generally do not survive the journey from the academic to the design setting without some major reinterpretation. Designers have no qualms about picking and choosing which recommendations to follow, or about simplifying what they see as excessively complicated calculations. Mainly, this is because designers are interested in the efficiency of the design process in ways that academic researchers may not be. One Caltrans engineer, discussing the textbook, explained:

> Sometimes when design references come out of academia, there's a tendency to be a little too theoretical and running more calculations than what we want to spend time on ... usually what happens [is] we get somebody aside that would take that report ... and look at it, and run a few examples on a few bridges, and say gee, if we just kind of ignore this part of it and just put in this little shortcut in here, that it will still end up with the right answer, maybe a little bit on the conservative side, but we'll be able to save several days of calculations.[67]

If designers were simply making these choices arbitrarily, or based solely on their own experience, there might be cause to question the usefulness of funding laboratory research in earthquake engineering; the connection between the two work settings would be tenuous at best. But this does not appear to be the case, because design engineers are not completely ignorant of the ways of academic research. Personal contact plays a crucial role in establishing this connection.

Faculty

Academic engineering faculty, particularly in very 'applied' fields like structural engineering, tend to play an intermediary role simply because of the positions that they hold. They have to seek research money and publish just like other academics, but they are also responsible for training the next generation of design engineers. Many faculty members at the

Structures Lab also have some previous experience as working designers. Because of this, their research is often very directly informed by design concerns, even if designers sometimes disagree with their specific recommendations. Since Caltrans is primarily oriented towards the design and maintenance of civil infrastructure, rather than basic research, the Structures Lab is perhaps more oriented than most towards producing results that will be immediately useful to design engineers. The analytical models and written reports produced by the laboratory are intended to facilitate this communication with Caltrans. However, as we have seen, these formalized representations seem to require a great deal of reinterpretation to be useful on the design floor. The transfer of knowledge between the two settings appears to depend much more upon a system of extensive face-to-face contact between Structures Lab researchers and Caltrans design engineers.

Some of these face-to-face contacts occur in the context of specific testing programs: researchers must work with the Caltrans engineers who oversee their research contracts. These engineers often travel to San Diego to observe tests, particularly those deemed to be particularly crucial. To some extent, they serve as conduits to communicate test results to others at Caltrans in a timely way. Faculty members also frequently make the 500-mile journey to Sacramento to consult with Caltrans engineers. One situation which often requires such a trip is when a research contract is being negotiated. These negotiations are very much a two-way process, in which faculty members have considerable power to shape the research agenda. One of the professors gave an example:

> Sometimes we think that they need to know more about a subject than they think they need to know ... we perhaps see a variety of things that not necessarily every Caltrans engineer sees as being significant design issues. An example of this is in the new project

> that we’re just going forward [with on] the behaviour of hollow columns. ... When we suggested this initially there was a feeling at Caltrans that it really wasn’t of great interest to them, because they basically ... build solid columns. And we point out there’s a lot of controversy at the moment about the performance of hollow columns in existing structures ... and that they’re looking towards the prospect of using hollow columns in some more major structures. ... There are some specific design issues there which we have some concerns about. ... [It changed] from being a very low priority to being quite a high priority [at Caltrans], after our discussions with them.[68]

Part of the reason academics have such an influence over the Caltrans research agenda is because they also play a role on legally-mandated oversight committees. In the early 1990s, following the Loma Prieta earthquake, Caltrans was required to initiate a continuing process of peer review of their design practices. This was accomplished by establishing panels composed of outside experts from both universities and private engineering firms. These panels work at several different levels: some are convened to oversee specific projects, while others serve in a general capacity, overseeing the development of design codes and practices. Each panel meets with Caltrans engineers on a regular basis. These meetings are a crucial location in which academics and designers meet and hash out their differences. They proceed on a nominally adversarial basis, in which panel members are free to point out various specific problems they see with a design standard or a design detail on a specific structure.[69] However, serious conflicts almost never arise. After some argument back and forth, most problems are resolved through consensus between panel members and Caltrans engineers. These meetings seem to have created a much stronger connection than previously existed between Caltrans and the larger community of seismic engineering practice.

The two principal faculty members associated with the Structures Lab have, over time, played prominent roles on many of these panels, and continue to do so. Between the panels and their research work, they sometimes commute to Caltrans headquarters in Sacramento on a weekly basis. In the process, they have also cultivated a wide range of informal contacts within the organization. Through these interactions, both in their role as formal advisors and in their role as trusted individuals, the professors have an impact on design practice at Caltrans which goes far beyond the simple reporting of research findings. This influence seems to depend largely upon their reputation within the organization as people who have an exceptionally deep understanding of seismic design issues, precisely because they are involved in cutting-edge research rather than routine design work. Even though their written recommendations may not be adopted wholesale by Caltrans engineers, the researchers ultimately have a great deal of power over how they are interpreted because of their prestige and personal connections within the organization.

In their work, both academic researchers and designers rely on a great deal of tacit knowledge gained through experience on the job. If knowledge gained through research is to be effectively exploited by designers, therefore, formalized representations of this knowledge, alone, will not be sufficient. This has clearly been a driving problem in relations between Caltrans and the research community. Before Caltrans had developed such close ties to researchers through funding academic research and organizing peer review panels, designers had to rely primarily on written sources to find out what was going on in earthquake engineering research and practice. Under these circumstances, many engineers outside Caltrans, including members of the

Governor's Board of Inquiry on the Loma Prieta earthquake, felt that the department had become cut off from the mainstream of engineering practice. Significantly, it was felt that this problem could best be resolved by establishing forums, like peer review panels, in which personal contact could take the place of reading articles. This need to go beyond formalism may characterize many cases of projection from laboratory to field.

Conclusions

This case study shows that projection, when analyzed in terms of local practices, can be a very complicated process, managed through heterogeneous means. The simplified representation in Figure 2 can only capture the chain of practices which connects laboratory testing in the Structures Lab to other work settings in the most schematic way. In this particular case, potential similarity relationships between the materials and representations used in different work settings are full of ambiguity. At each interface between work settings, this ambiguity is dealt with through the use of particularly flexible modes of representation, like computer models, as well as through hybrid objects which help resolve the tension between work settings in their physical form. In every case, however, the boundary objects are not, in themselves, sufficient to bridge the gap between work settings; human beings, with their complement of skills and tacit understandings, have to join them in their boundary crossing. This is why it makes sense to talk about projection in terms of the translation of practices across work settings. This is the most useful level of analysis for capturing the full complexity of the relationships between humans and machines which go into the process of projection.

The Division of Labour

While some authors have analyzed the distinctive role of laboratory technicians, and others have examined the division of labour in the laboratory setting as an element of scientific culture, I argue that the division of labour can play an important epistemological role as well. The methods of laboratory research are not invented in isolation from the rest of our culture. This is particularly clear in the Structures Lab, where skills in construction, electronics, hydraulics, and operating heavy machinery mingle with the practices of engineering science. In order for research to proceed, these bodies of practice have to be brought into the laboratory, and in order for laboratory work to have a coherent flow, they have to be integrated with one another. The knowledge that laboratory research produces depends upon this kind of integration of disparate sources of knowledge and skill. In the Structures Lab, it is usually the technicians who bring outside practices into the laboratory, and the graduate students who try to reconcile these bodies of practice with the practices of engineering research. Faculty members have their own role in integrating academic research and design practice.

A study of testing and projection brings these aspects of laboratory work to the fore, perhaps because testing often takes place as an integral part of a larger process of designing and manufacturing technology which occurs outside the laboratory. But these issues are not unique to testing. A central task of research in any scientific laboratory is to somehow bring ‘natural’ phenomena into the laboratory where they can be controlled and manipulated. This sometimes involves bringing outside bodies of skill into the laboratory. Some examples might be skills drawn from veterinary surgery which are important to biomedical research, or the wide variety of engineering skills necessary to build a working experimental apparatus in high-energy physics.[70] There is also a division of labour between graduate students and faculty in many laboratories, since representing the laboratory to the scientific community and to funding agencies often takes faculty members away from active involvement in research. Of course, laboratory work need not be divided up in any particular way. One would expect that each laboratory would develop its own characteristic division of labour. The important point is that the role of the laboratory in the production of knowledge cannot be fully understood without some analysis of where research skills come from, how different research tasks are distributed among the various actors in the laboratory, and how these actors manage to coordinate their activities.

Testing

When the activities of testing and projection are opened up and examined closely, they emerge as messy, contingent processes in which the management of ambiguity, rather than clear-cut relationships of similarity or dissimilarity, is the norm. This analysis of testing stands in clear contrast to that of MacKenzie and Pinch in this respect. Yet these authors are able to identify significant cases in which the credibility of test results clearly does depend on judgments of similarity or dissimilarity between test and use. The two perspectives can be reconciled, however. I would suggest that wherever the credibility of a test seems to depend on a clear-cut similarity relationship – or whenever an argument about testing revolves around the presence or absence of a similarity relationship – some crucial simplification has already taken place. In these cases, people have chosen to ignore the complexity of the local circumstances surrounding testing.

This can happen when a judgment of similarity is made, as when nuclear missile supporters claim that missile tests are credible because they are performed just like an actual launch. In the process they reduce the work of the people who remove the missile from its silo, take out its warhead, instrument it, and set it up for launch at the test range to necessary but epistemologically insignificant background activity. Judgments of dissimilarity, while they may bring out important aspects of testing practice, often depend upon a comparable assumption. Those who believe missile test are inaccurate, for example, assume that tests ought to be just like an actual launch. Practices that are particular to the testing process itself are therefore seen as deviations from the prescribed similarity relationship. Both forms of argument proceed on the assumption that the practices of testers ought to be left out when describing a successful test.

But this kind of simplification is not always necessary for a test result to be credible. Judgments of similarity and dissimilarity are likely to take on a particularly important role in two situations. First, when test results are taken up or debated in a social setting far removed from the test situation and the practices of testers, as in political debate or courtroom arguments. In these situations, most of the participants are not members of the same technical community as the testers, and do not share their nuanced understanding of the uses of test results. As a result, they may tend to rely on simple outward signs of similarity or dissimilarity between a test and the situation of use of a technology when judging the credibility of the test. Second, when both the testing procedure and the technology being tested are standardized to such an extent that they have become largely, but not completely, 'black boxed'. Such is the case in Pinch's example of the microphone test at a rock concert. In this situation, testing may be necessary to assess functionality, but the results are not debatable because the characteristics of a functioning system are already well known.

The complex nature of projection as practice, by contrast, is likely to come to the forefront under the sort of circumstances I have described here. That is, first of all, in situations where testing is oriented towards research and the development of new methods of analysis and design, rather than towards a simple functional evaluation of an established technology. It also becomes particularly significant in situations where test results are produced, analyzed, and applied within a relatively well-integrated technical community. The Structures Lab embodies both characteristics, since it does testing as research, and test results have significance primarily within the earthquake engineering community, which is probably more close-knit than many sub-fields of engineering. If test results were to become an object of political controversy or legal proceedings, which could certainly happen, arguments might well be made in terms of the similarity or dissimilarity between tests and earthquakes. But this has not happened yet, and it appears to be more important to the earthquake engineering community that researchers be able to give practical assistance to designers than that laboratory tests exactly simulate the effects of an earthquake.

Projection is always a process in which one social setting is linked to another. Under certain circumstances, important aspects of this connection can be described in terms of a similarity relationship between a test and the situation of use of a technology. However, to describe testing at the level of local work processes, or to explain how projection works within certain technical communities, it is necessary to focus on how the connection between social settings is embodied in a chain of practices. Examining such chains provides important insights into the ways in which knowledge and material practices are generated, transmitted, and put to use not only in the laboratory, but in technical communities in general. In particular, it highlights the division of labour and the need to coordinate work across different sites as important issues in modern technical practice. In the case of the Structures Lab, this approach makes it possible to understand how it is that construction workers' practical ways of understanding and working with concrete and steel can be put to use in the laboratory, and ultimately play a role in the development of the more abstract professional knowledge of academic researchers and design engineers.

Notes

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[1] This paper is based on interviews and participant observation conducted at the Structures Lab at various times over the course of the past three years, and on a series of interviews with engineers at the California Department of Transportation.

[2] This argument, which is described in detail below, was made first by Donald MacKenzie in 'From Kwajalein to Armageddon? Testing and the Social Construction of Missile Accuracy', in David Gooding, Trevor Pinch, and Simon Schaffer (eds), The Uses of Experiment: Studies in the Natural Sciences (Cambridge. MA: Cambridge University Press, 1989), 409-435; see also MacKenzie, Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance (Cambridge, MA: MIT Press, 1990), 340-381. Trevor J. Pinch elaborates upon this argument and coins the term 'projection' in his later article, ''Testing -- One, Two, Three ... Testing!': Toward a Sociology of Testing', Science, Technology, & Human Values, Vol. 18 (1993), 25-41.

[3] Competing Against Time: Report to Governor George Deukmejian from the Governor's Board of Inquiry on the 1989 Loma Prieta Earthquake (Sacramento: State of California, Office of Planning and Research, 1990).

[4] L.B., interview, 4 November 1997. Although all of the interview subjects waived anonymity, I have chosen to use full names only if the subject appears as an author of a publication cited elsewhere in the paper.

[5] See, for example, Karin Knorr-Cetina, The Manufacture of Knowledge: An Essay on the Constructivist and Contextual Nature of Science (Oxford: Pergamon Press, 1981); Bruno Latour and Steve Woolgar, Laboratory Life: The Construction of Scientific Facts, second edition (Princeton: Princeton University Press, 1986); Michael Lynch, Art and Artifact in Laboratory Science: A Study of Shop Work and Shop Talk in a Research Laboratory (London: Routledge & Kegan Paul, 1985); Sharon Traweek, Beamtimes and Lifetimes: The World of High Energy Physicists (Cambridge, MA: Harvard University Press, 1988); Chandra Mukerji, A Fragile Power: Scientists and the State (Princeton: Princeton University Press, 1989).

[6] MacKenzie (1989, 1990) and Pinch, op. cit. note 2.

[7] Ibid.

[8] MacKenzie (1989), op. cit. note 2, 411 (emphasis in the original).

[9] H.M. Collins, 'The TEA Set: Tacit Knowledge and Scientific Networks', Science Studies, Vol. 4 (1974), 165-186; Collins, 'The Seven Sexes: A Study in the Sociology of a Phenomenon, or the Replication of an Experiment in Physics', Sociology, Vol. 9 (1975), 205-224; Collins, 'Son of Seven Sexes: The Social Destruction of a Physical Phenomenon', Social Studies of Science, Vol. 11 (1981), 33-62. These articles are summarized and tied together in Collins, Changing Order:

Replication and Induction in Scientific Practice, second edition (Chicago: University of Chicago Press, 1992).

[10] MacKenzie, op. cit. note 2, 414.

[11] Although MacKenzie refers to Edward Constant's work on technological communities and 'traditions of technological testability' in his theoretical discussion, these issues are not elaborated on in his case study. See Constant, 'Scientific Theory and Technological Testability: Science, Dynamometers, and Water Turbines in the 19th Century', Technology and Culture, Vol. 24 (1983), 183-198 and Constant, The Origins of the Turbojet Revolution (Baltimore: Johns Hopkins University Press, 1980).

[12] See Collins (1974), op. cit. note 9, and Collins (1992), op. cit. note 9, 51-78.

[13] See Strauss, 'A Social World Perspective', Studies in Symbolic Interaction, Vol. 1 (1978), 119-128. For examples of how this approach has been applied to science and technology, see Rob Kling and Elihu Gerson, 'Patterns of Segmentation and Intersection in the Computing World', Symbolic Interaction, Vol. 1 (1978), 24-43; Gerson, 'Scientific Work and Social Worlds', Knowledge, Vol. 4 (1983), 357-377; Susan Leigh Star and James Griesemer, 'Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-1939', Social Studies of Science, Vol. 19 (1989), 387-420; Joan Fujimura, 'Crafting Science: Standardized Packages, Boundary Objects, and 'Translation'', in Andrew Pickering (ed.), Science as Practice and Culture (Chicago: University of Chicago Press, 1992). A useful overview of the approach is given in Karin Garrety, 'Social Worlds, Actor-Networks and Controversy: The Case of Cholesterol, Dietary Fat and Heart Disease', Social Studies of Science, Vol. 27 (1997), 727-773.

[14] Strauss, op. cit. note 13, 122-123.

[15] Star and Griesemer, op. cit. note 13, 411. Here they draw on the work of Chicago school sociologists Robert Park and Everett Hughes.

[16] Ibid., 393 (emphasis in the original). Also see Fujimura, op. cit. note 13, for an elaboration of this idea through the concept of 'standardized packages'.

[17] This sort of analysis has certain obvious parallels with other work, such as the actor network approach of Bruno Latour, Michel Callon, and others. However, these authors are centrally concerned with issues of technoscientific change, and in the exercises of power, translations of terms, and simplification and 'black boxing' that go into the construction of sociotechnical networks. See, for example, Latour, Science in Action (Cambridge, MA: Harvard University Press, 1987) and Callon, 'Society in the Making: The Study of Technology as a Tool for Sociological Analysis', in Wiebe Bijker, Thomas Hughes, and Trevor Pinch (eds), The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology (Cambridge, MA: MIT Press, 1987), 83-103. While these concerns could be brought into my analysis, I am more interested in examining the detailed workings of a well-established network. I believe this approach makes it possible to examine the normal work of testing in greater depth. .

[18] I thank Steven Epstein for pointing this out to me.

[19] Pinch, op. cit. note 2, 26.

[20] See Latour, op. cit. note 17, 2-3, 130-131, and Callon, op. cit. note 17, 93-95.

[21] The participants in these work settings may share a common way of understanding technology that is similar to an 'object world', as described by Louis L. Bucciarelli in relation to engineering design. Bucciarelli, Designing Engineers (Cambridge, MA: MIT Press, 1994).

[22] Peter Galison, Image and Logic: A Material Culture of Microphysics (Chicago: University of Chicago Press, 1997), 781-844.

[23] This term was introduced to me by M.J. Nigel Priestley, interview, 11-7-97.

[24] This is generally similar to what Glenn Bugos has called 'acceptance testing'. See Bugos, 'Manufacturing Certainty: Testing and Program Management for the F-4 Phantom II', Social Studies of Science, Vol. 23 (1993), 265-300.

[25] MacKenzie (1989), op. cit. note 2. See also the tests described in Bruno Latour, trans. Catherine Porter, Aramis, or The Love of Technology (Cambridge, MA: Harvard University Press, 1996) and in John Law and Michel Callon, 'The Life and Death of an Aircraft: A Network Analysis of Technical Change', in Wiebe Bijker and John Law (eds), Shaping Technology/Building Society: Studies in Sociotechnical Change (Cambridge, MA: MIT Press, 1992), 21-52.

[26] An excellent historical example of this sort of testing can be found in Nathan Rosenberg and Walter Vincenti, The Britannia Bridge: The Generation and Diffusion of Technological Knowledge (Cambridge, MA: MIT Press, 1978). The bridge featured an unprecedented tubular design, so an extensive series of tests was carried out in order to find the fundamental causes of failure in metal tubes, and to see which configurations were most stable. The results of this research subsequently proved useful in many different areas of engineering.

[27] Knorr-Cetina and Latour and Woolgar, op. cit. note 5, are all consistent with this trend. Lynch, op. cit. note 5, looks at the work of a group of graduate students, but not in the context of an overall division of labour in the laboratory. In part, this lack of consideration of role differentiation could stem from the relatively small scale of the laboratories studied in these works. Traweek and Mukerji, op. cit. note 5, are two notable exceptions to the general trend, and both deal with relatively large-scale laboratories in high energy physics and oceanography, respectively.

[28] Steven Shapin, 'The Invisible Technician', American Scientist, Vol. 77 (1989), 554-563 and Shapin, A Social History of Truth: Civility and Science in Seventeenth-Century England (Chicago: University of Chicago Press, 1994), 355-407.

[29] Mukerji, op. cit. note 5, 125-145. For another contemporary study focusing on technicians, see Julian Orr, Talking About Machines: An Ethnography of a Modern Job (Ithaca, NY: Cornell University Press, 1996).

[30] Stephen Barley, 'Technicians in the Workplace: Ethnographic Evidence for Bringing Work into Organization Studies', Administrative Science Quarterly, Vol. 41 (1996), 404-440. For a more detailed discussion of laboratory technicians, see Barley and Beth Bechky, 'In the Backrooms of Science: The Work of Technicians in Science Labs', Work and Occupations, Vol. 21 (1994), 85-126.

[31] Barley, op. cit. note 30, 418.

[32] Ibid., 422.

[33] Ibid., 420.

[34] This term is proposed by Constant, op. cit. note 11.

[35] These methods are summarized in Egor P. Popov, 'Experiment as an Aid to Structural Seismic Design', Experimental Mechanics, Vol. 26 (1986), 194-208. The reasons for the widespread use of quasi-static testing are discussed in some detail in Robert T. Leon and Gregory G. Deierlein, 'Considerations for the Use of Quasi-Static Testing', Earthquake Spectra, Vol. 12 (1996), 87-109.

[36] This method is also sometimes referred to as 'pseudo-static' testing. Popov, op. cit. note 35.

[37] In addition to the test methods discussed here, a hybrid method known as 'pseudo-dynamic' testing has recently been developed, which uses multiple hydraulic actuators controlled by a computer program which simulates the motion that a structure would undergo during a specific earthquake, but at the slow speed of a quasi-static test. This method is still being refined and is not yet in widespread use. See F. Seible, G.A. Hegemier, A. Igarashi and G.R. Kingsley, 'Simulated Seismic-Load Tests on Full-Scale 5-Story Masonry Building', ASCE Journal of Structural Engineering, Vol. 120 (1994), 903-924.

[38] Leon & Deierlein, op. cit. note 35.

[39] Leon & Deierlein, op. cit. note 35, 87.

[40] This research is presented in Anthony V. Sánchez, Frieder Seible and M.J. Nigel Priestley, Seismic Performance of Flared Bridge Columns, Structural Systems Research Project Report No. 97/06 (La Jolla: University of California, San Diego, Division of Structural Engineering, 1997).

[41] P.N., interview, 4 November 1997.

[42] The smaller scale of the test specimens may also be relevant here, but this technician did not see it as a major factor.

[43] F. Seible, interview, 7 November 1997.

[44] Priestley, op. cit. note 23.

[45] M.B., interview, 19 March 1997.

[46] C.L., interview, 10 March 1997.

[47] Seible, op. cit. note 43.

[48] P.N., op. cit. note 41.

[49] Ibid.

[50] C.S., interview, 7 April 1997.

[51] Ibid.

[52] Ibid..

[53] M.J.N. Priestley, interview, 19 November 1996.

[54] Ibid.

[55] Ibid.

[56] Priestley, op. cit. note 23; F. Seible, interview, 27 February 1997.

[57] Priestley, op. cit. note 53.

[58] M.J.N. Priestley, F. Seible and C.M. Uang, The Northridge Earthquake of January 17, 1994, Damage Analysis of Selected Bridges, Structural Systems Research Project Report No. 94/06 (La Jolla: University of California, San Diego, Division of Structural Engineering, 1994).

[59] F. Seible, interview, 8 November 1996.

[60] See Joseph O'Connell, 'Metrology: The Creation of Universality by the Circulation of Particulars', Social Studies of Science, Vol. 23 (1993), 129-73; Simon Schaffer, 'Late Victorian Metrology and its Instrumentation: A Manufactory of Ohms', in Robert Bud and Susan E.

Cozzens (eds), Invisible Connections: Instruments, Institutions and Science (Bellingham, WA: SPIE Optical Engineering Press, 1992), 23-56; and Latour, op. cit. note 16, 250-254.

[61] Seible, op. cit. note 43.

[62] Ibid.

[63] Anthony Sánchez, interview, 23 October 1996.

[64] Interview with S.M., a Caltrans engineer, 28 August 1997. This informant gave as an example a program developed by researchers at the Structures Lab called COLRET, which is currently used at Caltrans, but in a substantially altered form. The program is described in Y.H. Chai, M.J.N. Priestley and F. Seible, Flexural Retrofit of Circular Reinforced Bridge Columns by Steel Jacketing: COLRET - A Computer Program for Strength and Ductility Calculation, Structural Systems Research Project Report No. 91/05 (La Jolla: University of California, San Diego, Division of Structural Engineering, 1991).

[65] For example, M.J.N. Priestley, F. Seible and Y.H. Chai, Design Guidelines for Assessment, Retrofit and Repair of Bridges for Seismic Performance, Structural Systems Research Project Report No. 92/01 (La Jolla: University of California, San Diego, Division of Structural Engineering, 1992).

[66] M.J.N. Priestley, F. Seible and Gian Michele Calvi, Seismic Design and Retrofit of Bridges (New York: John Wiley and Sons, 1996).

[67] R.Z., interview, 25 August 1997.

[68] Priestley, op. cit. note 23.

[69] This description is based primarily upon an interview with C.S., a senior designer at a major engineering firm who has served on several peer review panels, 28 May 1997.

[70] On the latter, see Galison, op. cit. note 22.

Figures

Figure 1. The laboratory as a construction site. This photograph shows a technician and a graduate student pouring concrete into wooden forms to cast a test specimen.

Figure 2. Projection at the Structures Lab: the chain of practices. This diagram leaves out some complexities in the interest of clarity.

Figure 3. Configuration of a typical column test. The column is approximately 5 meters tall. Reproduced from Anthony V. Sánchez, Frieder Seible and M.J. Nigel Priestley, Seismic Performance of Flared Bridge Columns, Structural Systems Research Project Report No. 97/06 (La Jolla: University of California, San Diego, Division of Structural Engineering, 1997), 22.

Figure 4. Hysteresis graph for unflared column test, showing the close correlation that can often be obtained between analytical predictions and test results. Reproduced from Anthony V. Sánchez, Frieder Seible and M.J. Nigel Priestley, Seismic Performance of Flared Bridge Columns, Structural Systems Research Project Report No. 97/06 (La Jolla: University of California, San Diego, Division of Structural Engineering, 1997), 585.