STABILITY RELATED DETERIORATION OF STRUCTURES

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ABSTRACT

The definition of structural deterioration can be expanded to include any problems that occur in existing structures as opposed to new designs. With this definition, deterioration related to stability includes not only the common conception of physical damage and corrosion, but also problems resulting from code changes and even errors in design or construction. The causes of damage and environmental deterioration can be divided into categories of everyday usage and catastrophic events that impact to various degrees, buildings, bridges, offshore structures and lifeline structures. Methodologies for assessment are in developmental stages and considerably more research is still required for evolving reliable methods for assessment and rehabilitation.

As an example of research directed toward understanding the details of deterioration, the significant role that local buckling or dents play in causing catastrophic fracture under cyclic loads is illustrated by the results of a pilot test program using rectangular tubes subject to axial loads. Although axial displacement range, mean displacement and load rate may all have an influence on the number of cycles to fracture, the single factor that separates members that have hundreds of cycles to fracture from those that fracture in fewer than 40 cycles is the presence of a local buckle. The formation of local buckles requires higher axial displacement for tubes with lower width/thickness ratios. Therefore, recent code changes that specify more restrictive width/thickness ratios for braces in seismic design will enhance the performance of tubular members.

INTRODUCTION

Numerous articles have appeared in public and technical literature describing the magnitude of the nation's deteriorating infrastructure problem. The most common problems mentioned are the high percentage of bridge structures with critical or moderate need for rehabilitation and buildings that have sustained damage during an earthquake or are no longer in compliance with modern seismic criteria. Structural engineers are aware of many more specific examples of different types of structures in need of rehabilitation for a wide variety of reasons.

During the 50th Anniversary Conference of the Structural Stability Research Council in 1994, there was a workshop on Deteriorated Structures. Participants from various parts of the world discussed a broad range of problems associated with deterioration. The first part of this paper that deals with the broad aspects of deterioration is based on ideas presented in the workshop. The second part of the paper presents the conclusions of a pilot test program to determine the cause of fractures found in hollow structural section (HSS) braces in the Northridge Earthquake and the factors that may influence the behavior of HSS braces.

TYPES AND CAUSES OF DETERIORATION

In the workshop discussion concerning the types of deterioration that can occur in structures, it was concluded that more than just physical damage should be considered. The topic should be broadened in scope to include the consideration of any stability problems that can occur in existing structures as opposed to new designs. With this extended definition, the following types of deterioration that influence stability can be identified.

DAMAGE - Local denting or out-of-straightness that produces a condition that members or the structure are no longer within original construction tolerances.

ENVIRONMENTAL - Conditions that lead to loss of cross section in members or alterations of joint characteristics that change the boundary conditions of members.

LEGAL - Changes in applicable codes or in the function of the structure that produce different loads or design criteria.

ERRORS - Either design or construction errors that are not detected until after the structure is built.

Several causes of damage or environmental types of deterioration can be identified. These are divided into categories of everyday usage and catastrophic events.

EVERYDAY USAGE

REPETITIVE LOADS - This includes cyclic loads from equipment, random load variations or other repetitive loads that can produce fatigue conditions. The resulting cracks may influence the section or boundary properties to the extent that stability is degraded in a member or in a structure as a whole.

CORROSION - Environmental conditions can lead to loss of section or deterioration of joints.

LACK OF MAINTENANCE - This could lead to corrosion, build up of material in joints or structural misalignments due to use of equipment (e.g. cranes)

CATASTROPHIC

IMPACT - Impact damage occurs from moving vehicles or falling objects that locally dent and/or permanently bend a member.

SINGLE OVERLOAD - Hurricanes, tornados or unusual vehicle or equipment loads that produce permanent local or general member buckling.

SEISMIC EVENT - Severe horizontal cyclic loads on the structure that produce buckling or fracture in members.

FIRE - Twisting or bending of members beyond construction tolerances but not to the degree where replacement is obviously required.

BLAST - Explosions that occur either from industrial accidents or intentional bombing that produce permanent distortions in the structure.

Deterioration in various forms could occur in many types of steel structures. However, the frequency of types or causes of damage is more prevalent in different structure categories.

BUILDINGS - Exposed columns in industrial buildings and parking structures are frequently subject to vehicle impact and are potentially subject to environmental deterioration. Industrial buildings are also subject to maintenance, overload or cyclic load problems. Any type of building can experience fire, blast or seismic damage. Seismic damage is the most prevalent and most commonly affects braces and joints in steel buildings.

BRIDGES - Vehicle impact frequently occurs in members of bridges. Corrosion and maintenance problems are also frequently encountered. Other source of damage often affect bridge supports and foundations, but these are not within the scope of stability of metal structures.

OFFSHORE STRUCTURES - Work platforms are subject to any of the types or causes of damage that have been identified.

LIFELINE STRUCTURES - Seismic events can damage pipelines and towers. Pipelines are also subject to corrosion or accidental impact from moving equipment. As exposed structures, towers are subject to environmental damage.

Any type of steel structure could require evaluation due to errors or changes in loadings and applicable codes. This is a particular problem with older bridge structures and buildings in seismic regions.

Bridges were commonly designed for 30 to 50 year lives. Bridge loadings have increased considerably over this period and many existing bridges are over 50 years old. As in the case of buildings, many of these older structures have survived and continue to function with loadings well beyond their original design loads because of very conservative design practices.

Starting 50 years ago, offshore structures were originally designed for a 30 year life and to withstand a 25 year wave. Now there is an interest in extending the life of older platforms and the design criteria is a 100 year wave. With modern analysis methods and refined criteria, older structures can frequently be shown to still be adequate.

ASSESSMENT

Once it has been determined that a member or structure is in a deteriorated condition, a decision must be made on selecting one of three options:

1. Leave it as is since it can perform its function in a satisfactory manner.

2. Rehabilitate to improve its condition so it will perform satisfactorily.

3. Replace the member, subassemblage or entire structure.

Although analysis for re-rating bridges has been common practice for many years, general methodologies for assessment are still in formative stages. A draft of a section of API RP2A (Offshore Platforms) has been prepared that presents a general strategy. Similar studies for cracks in bridge structures are also underway. Essentially the strategy consists of a sequence of classifications of the severity of deterioration and its consequences. Each stage increases in complexity. If the results are satisfactory in any stage, the deterioration is dismissed. If not, proceed to the next stage. The stages are:

1. Gather data to document the severity of deterioration.

2. Screen the information and make an experience judgement as to whether the deterioration might be severe enough to limit the function of the structure.

3. Consider the effects at working stress levels.

4. Perform an ultimate strength analysis. Simple and conservative analyses are used first and increasingly complex analyses are used if necessary to demonstrate a margin against failure; e.g.

    a) Elastic analysis without safety factors and using mean yield strengths.

    b) Detailed local analysis if few members are involved.

    c) Global analysis (eg. pushover in the case of offshore platforms)

5. Design the required rehabilitation or replacement.

At any stage the economics of proceeding must be considered. It may be less expensive to rehabilitate or replace than to proceed with the assessment.

Parameters to be considered in the evaluation and assessment are the location of the deterioration in a member and in the structure, severity, structural type (e.g. degree of redundancy), consequences of failure. Included in the latter are considerations of whether the structure is occupied, possible evacuation of personnel with adequate storm warnings, potential environmental pollution and economic importance of the structure.

Although knowledge of the reserve strength of an individual member is important, primary consideration must be given to its effect on the total structure. Therefore, information on its altered stiffness must be known for an elastic analysis and nonlinear characteristics are required for an ultimate strength analysis. If there are many sources of out-of-tolerance in the structure, they can add up to potentially dangerous situation. In an ultimate strength analysis, there is the possibility of a complex analysis to determine a beta or reliability factor for the structure. Although this is an option for engineering decisions, reference to reliability or probability of survival should be avoided when dealing with the public; the public wants a clear statement that the unrepaired or rehabilitated structure is reliable.

Inspection is an important part of the assessment process especially when deterioration is caused by everyday events. In any assessment, it is important to determine the root cause of deterioration so that simple repair does not lead to a recurring problem. As an example not directly related to stability, a crack caused by overload during installation can be rewelded, but fatigue cracks should not be simply rewelded.

REHABILITATION

Tubular members have been rehabilitated with internal grouting and external sleeves or clamps to encase the damaged section with grout. Fiber-reinforced concrete and shotcrete have been used to encase buckled web members in open-web joists to obtain stable hysteresis loops. The objective of grouting is to stabilize local buckles or dents so they do not grow under subsequent static or cyclic loads. However, research has shown that there is a limiting dent depth and out-of-straightness beyond which the original strength of the member cannot be regained. Grout has also been used to reinforce connections.

In bridges, rehabilitation frequently involves increasing capacities and widths in addition to repair of physical deterioration. Several strategies to eliminate stability problems from both bridge and offshore experiences can be mentioned. These include schemes to increase strength or reduce loads.

Replace members with higher strength steel
Add additional braces to compression members
Post-tensioning schemes
Internal or external grout
Insert piles in tubular members with grouted annular space
Intentionally flood submerged tubular members to reduce external pressure
Reduce loads by removing unnecessary appendages that catch drag forces

NEEDED RESEARCH

The whole area of dealing with deteriorated structures is still in the early stages of development, and considerable research is needed for economical and efficient assessment and rehabilitation.

EXPERIMENTAL - Tests are required to determine the behavior and reserve capacity of various types of deterioration for different types of members. These tests are needed to provide a baseline for analytical predictors. Tests are also required to provide information on innovative methods for repairing deterioration.

ANALYTICAL - Further research is needed to develop reliable, efficient and economical analytical methods to determine reserve capacities and behavior of damaged members of various cross sections. The complete nonlinear behavior of members, including the descending branch, must be known in order to conduct collapse analyses of the entire structure.

PRACTICE - Information is needed to classify which dents (severity and location) or other types of deterioration can be accepted. General methodologies must be developed for assessing older structures. A good exchange of information is required so that successful methods of assessment and rehabilitation are widely known.

HSS BRACE UNDER CYCLIC AXIAL LOAD

As an example of research directed toward determining the causes of catastrophic damage, the results of a pilot tests program on rectangular hollow structural sections (HSS) are presented. This test program was motivated by the observation of a fracture in a 10"x10"x3/8" HSS bracing member with a flat width to thickness ratio (b/t) of 23 in the Northridge Earthquake of January 1994. The test program consisted of testing two thicknesses of 5"x2" HSS under axial displacement with ends pinned for column buckling about the weak axis. The properties of the test specimens are summarized in Table 1.

TABLE 1 - HSS TEST SPECIMEN PROPERTIES

SIZE	b/t	KL/r	F_y ksi	P_y kips	P_{stub} kips
5x2x1/8"	36	83.5	46.1	71.0	77.7
5x2x3/16"	23	86.4	57.0	127.2	161

The size, b/t and column slenderness (KL/r) are based on nominal dimensions. The yield stress (F_y) and the measured stub column strength (P_{stub}) were obtained in static tests while the yield load (P_y) is calculated from the static yield stress and the actual HSS dimensions. The fact that the stub column tests are higher than the yield load reflects enhanced yield properties in the corners of the HSS and indicate that local buckling occurred in the strain hardening range.

The AISC Specification defines a thin-walled HSS under uniform compression as having a b/t that exceed $238/\sqrt{F_y}$, or in this case 35 for the thin HSS. The recent AISC Seismic Provisions limit b/t to $110/\sqrt{F_y}$ or about 15 for both of the two sizes. Therefore, the thicker of the test specimens is similar to the HSS observed after the earthquake and would have been acceptable under the older code provisions, but neither HSS would be acceptable under the newer provisions.

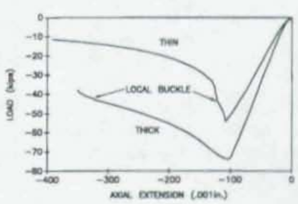

FIG. 1 - AXIAL LOAD-DISPLACEMENT

Both tube sizes were initially tested as columns under very slow monotonic axial loading. The resulting load vs. axial displacement curves are shown in Fig. 1. Since the column slenderness is almost identical for the two sizes, overall column buckling occurs at essentially the same axial displacement. Subsequent local buckles, however, develop at less displacement in the thinner HSS. In the cyclic test program, axial displacement limits were at 0.200" where only the thin HSS formed a local buckle and at 0.400" where both HSS had local buckling.

The variables in the cyclic test program were the axial displacement range, the mean axial displacement and the rate of loading as determined in the period for a cycle. A similar pattern of behavior was observed in most of the cyclic tests. Column buckling is followed by a local buckle which leaves "horns" at the corners. After several cycles with tension excursions, cracks initiate at the HSS corners on both horns and propagate through the thickness and away from the corners in subsequent cycles. As section is lost at the cracks resulting in an eccentric load, the lateral deflection reverses during the tension part of the cycle but return to the original direction during compression, producing a snap-through behavior. Eventually the crack pops across the local buckle, resulting in increased lateral deflection that creates a large enough eccentricity to reverse the direction of column buckling in the subsequent compression. Table 2 presents the displacement range, the test identification number, the cycle period and the number of cycles for a full fracture across the width of the section.

The most significant conclusion from the tests is that Test #4, which buckled as a column but did not form a local buckle, sustained over 500 cycles of loading without developing a crack. All other tests where local buckling did occur failed in 41 or fewer cycles.

TABLE 2 - CYCLES TO FRACTURE

DISPLACEMENT (in.)	THICK			THIN		
	TEST	PERIOD (s)	CYCLES	TEST	PERIOD (s)	CYCLES
-.200, +.200				7	480	**32**
	4	16	**500+**	8	16	**32**
-.300, +.300				10	2	**27**
-.400, +.200	2	40	**31**			
	5	5	**34**			
	4a	5	**41**		PRELOAD	
	3	2	**40**	9	2	**18**

Although the influence of local buckling is the most significant conclusion in these tests, several secondary conclusion may be made by comparing various tests. Some of these are intuitive, but they have been quantified in these tests.

Tests #3 & 9 - high b/t leads to lower fracture life for the same displacement range and period.

Tests #7,8 & 9 - higher displacement range leads to lower life.

Test #10 & 9 - mean displacement may have an effect. However, Test #10 was an exception to the general behavior in that a reversal in buckling direction occurred after the cracks initiated but before the pop across the face. A local buckle then formed on the other side, followed by crack initiation, pop and another direction reversal. Cycling on both faces may account for the longer life than Test #9, which had the same range. Test #10 was the only test with full tension yield.

Tests #4a & 5 - precycling may be beneficial. Test #4a was a continuation of Test #4, but with higher displacement range that corresponded to Test # 5 in both displacement range and period.

Tests #7 & 8 - variations in loading rates at periods greater than 16 seconds have no influence on fracture life.

Tests #2,5 & 3 - low periods have a beneficial influence on fracture life.

These pilot tests demonstrate that the only important parameter in determining whether HSS braces will survive a seismic event is the formation of local buckles. The column tests can serve as benchmarks for analytical studies to determine the axial displacements at which local buckles form as a function of b/t, KL/r and the yield strength.

CONCLUSIONS

Several conclusions can be made from the overall discussion in this paper.

1. With an extended definition to include stability considerations in existing structures, "deterioration" can take many forms in addition to damage and corrosion.

2. There are a variety of everyday and catastrophic causes of deterioration that affect different types of structures to a greater or lesser extent.

3. Assessment procedures are in various stages of development in industries concerned with different types of structures.

4. Rehabilitation methods require ingenuity and research.

5. Detailed research on behavior is required to develop guidelines to deterioration causes, assessment procedures and rehabilitation schemes.

6. There is a critical need for dissemination of information by practitioners who have had success in assessment and rehabilitation methods.