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Experimental investigation of short steel columns with localized corrosion

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ABSTRACT

To investigate the effect of corrosion on the axial capacity of steel bridge piles, a total of 13 H-shaped short columns were tested under monotonic axial load. The columns were machined to simulate different degrees and patterns of corrosion. The remaining axial capacity of the deteriorated members was assessed. To simulate the corrosion, webs and flanges were milled near the mid-height of the columns to reduce their thicknesses. The experimental results were compared to the axial capacities predicted by the design provisions of the American Institute of Steel Construction (AISC), American Association of State Highway and Transportation Officials (AASHTO), and American Iron and Steel Institute (AISI). The results of this study indicate that the degree of flange corrosion is the single factor that has the most significant effect on the column capacity. Other factors, including unsymmetry of the corrosion pattern or reduction of the flange width had a minor influence on the capacity. The results also indicate that, among the design methods considered, the effective width method recommended by AISI provides the best prediction of the capacity of severely deteriorated steel columns.

1. Introduction

Steel 'H' piles are widely used for bridge construction throughout the United States. These members are common in older, 'off-system' bridges that cross small creeks or seasonal streams. Many of these structures have been in service for over 50 years. Extended exposure to repeated wetting and drying commonly results in corrosion of these piles as shown in Fig. 1. Typically, this corrosion is localized within a zone of a few feet above and below the water or soil surface as shown in the figure. While the corrosion is typically limited in extent, it can be quite severe resulting in near-total loss of cross-section in some cases. Field observations indicate that corrosion occurs in the form of severe reduction of the thickness of the flanges and web of the H piles. In extreme cases this may result in the formation of small perforations or voids in the web and a reduction of the flange width at some cross-sections along the length of the pile.

This severe degradation has raised concerns among state Departments of Transportation (DOTs), bridge engineers, and maintenance crews regarding the integrity of the severely deteriorated columns. According to a recent survey of state DOTs [1] that was conducted by the research team corrosion of steel piles was cited as a frequent problem by 26% of respondents and as an occasional problem by 48% of respondents. While deterioration of bridge piles typically triggers maintenance and repair activities, evaluation of the pile condition is often largely qualitative. Further, since corrosion can be quite severe, and highly non-uniform, prediction of the remaining capacity of the pile can be particularly challenging. One approach is to treat the corrosion as uniform along the length of the pile. Using this approach, one could predict the capacity using existing design models based on the minimum cross-section dimensions of the deteriorated pile. In some cases corrosion may cause the web or flange to become slender leading to local buckling as the dominant failure mode. On the other hand, if the flange and web are non-slender, the localized corrosion may result in the formation of a localized weak region at the corroded section resulting in global buckling of the pile at a reduced load. Similar patterns of corrosion can also form in short wide-flanged columns in various other types of structures including industrial facilities, chemical processing plants, and marine structures.

Beaulieu et al. [2] evaluated the axial compressive strength of corroded steel angles that were used in transmission towers. A comparison of the measured capacities with those predicted by existing design equations indicated that the current codes did not accurately predict the capacity of the corroded members. Saad-Eldeen et al. [3,4] conducted an experimental and numerical investigation on the ultimate strength of severely corroded steel box girders that are used in ship structures. They also developed and implemented a new stress–strain model to account for the degradation of the steel mechanical properties due to corrosion.

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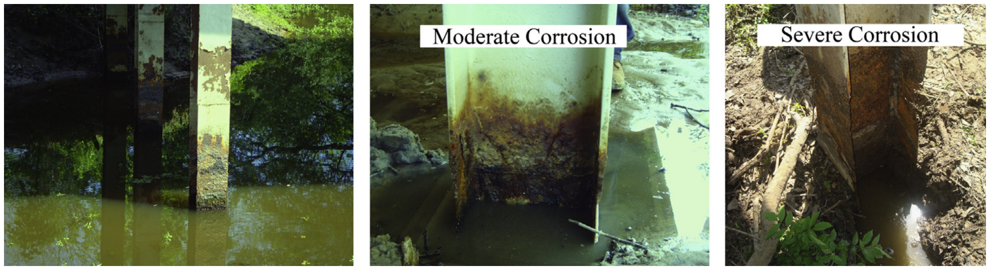

Fig. 1. Deterioration of steel bridge piles.

Jiang and Soares [5,6] studied the effect of pitting corrosion on mild steel plates under uniaxial and biaxial compression. They developed a semi-empirical method that is based on the results of a non-linear finite element analysis to predict the compression capacity of rectangular plates. Liu et al. [7] simulated the corrosion of wide-flanged compression struts by locally reducing the flange widths. The compression struts were subsequently repaired using grout-filled FRP jackets. Based on their test results, the research team proposed a simplified design approach to predict the capacity of damaged and repaired compression struts in truss bridges.

To predict the capacity of columns with slender elements, the critical local buckling loads of the web and flange must be determined. However, the local buckling capacity of one element is related to the rotational restraint provided by the adjacent elements, which is a function of the slenderness of those elements. AISC [8] and AASHTO [9] consider the effect of localized slenderness by introducing a reduction factor, Q. However, this factor does not consider web-flange interaction [10,11]. The AISI Effective Width Method (AISI-EWM) [12] computes the axial capacity of sections with slender elements by calculating a reduced width and assuming a uniform stress distribution for those elements. On the other hand, the AISI Direct Strength Method (AISI-DSM) [12] evaluates the strength of members with slender elements as a whole for different buckling modes in lieu of element-by-element assessment. Web-flange interaction in thin-walled columns and the interaction between local buckling, distortional buckling, and Euler buckling modes (lateral and torsional) were evaluated experimentally and design recommendations were provided by Schafer [13]. Comparison between the predicted axial capacity of W sections with slender elements as obtained from nonlinear finite element analysis with the predicted capacity as obtained from the design provisions of AISC, AASHTO, and AISI revealed that there were discrepancies in the results [14]. However, the AISI-EWM provided the most accurate predictions of the column capacity. Seif and Schafer investigated the interaction between the web and flange in the elastic range using the finite strip method [11]. They introduced a unique plate-buckling coefficient for hot-rolled sections that considered the effect of the slenderness of the adjacent elements. Also based on the distribution of strain-energy in the non-uniformly strained cross-section, Seif and Schafer introduced an improved method to the AISI-DSM to predict the local buckling strength of columns with slender elements [15]. In a subsequent study a modified EWM was proposed for structural steel based on the results of a series of numerical studies on a range of short and long columns [16]. All of these studies focused on prismatic members and did not consider the influence of a localized, severe reduction of the cross-section.

The AISI-EWM provisions consider the effect of perforations in the web on the overall capacity of members with slender elements. However, AISI-DSM does not recognize columns with perforations as pre-qualified columns. As such Moen and Schafer [17] investigated the influence of slotted holes in the web of C-channels under compression. They suggested several methods to predict the axial capacity of cold-formed steel columns using the AISI-DSM [18]. However, finite element analysis is required to calculate the critical elastic buckling loads for columns with holes.

2. Research significance

The initial step in the inspection and maintenance of corroded steel bridge piles and columns is to assess the remaining capacity of the deteriorated members. This requires a detailed understanding of the behavior of non-prismatic H-piles under axial compression, which has not been previously studied. This paper presents the results of an experimental study on a series of short columns with simulated localized degradation to assess the failure modes and remaining capacity of the severely corroded compression members. The influence of different patterns of corrosion on the column behavior is studied. The remaining axial capacities of the tested columns are calculated using the current design specifications and compared to the measured capacities. Since similar types of corrosion occur in short steel columns in a wide range of structure types, the research findings are broadly relevant.

3. Test specimens

To investigate the effect of partial degradation on the axial capacity of steel piles, a series of small-scale tests were conducted in two phases. To ensure that the behavior of the test columns is similar to that of typical steel H-piles and short columns, the aspect ratio of the cross section, flange, web, and member slenderness of the specimens were selected to be similar to those of typical HP sections that are commonly used as bridge piles. A total of thirteen 813 mm long W4 × 13 (US designation) columns were tested under axial compression. In phase I, seven columns were tested to evaluate the effect of the flange and web corrosion on the capacity of the columns as outlined in Table 1 and illustrated in Fig. 2. One of the columns was tested as an uncorroded control column. For the remaining columns, localized corrosion was simulated by milling the flanges and the web along a 305 mm long region near the mid-height of the columns. The webs were machined to simulate three different levels of corrosion 0%, 30%, and 60% loss of the thickness. The flanges were machined to simulate 0%, 50%, and 75% thickness loss. Four columns were machined to investigate the effect of flange and web corrosion independently while two columns were milled to investigate the effect of simultaneous flange and web corrosion. Due to practical limitations the fillet region between the web and flanges remained un-milled. Each column was assigned a unique two-part identifier that indicates the percent reduction of the flange and web thicknesses.

In phase II, the columns were machined to represent real corrosion patterns that were observed in the field as outlined in Table 2 and illustrated in Fig. 2. In this phase the reduction of the thickness of the flanges and web remained constant at 75% and 60%, respectively. To simulate realistic severe corrosion conditions, four of the columns were machined with a 51 mm void in the web at mid-height. Severe corrosion of the flanges was simulated by machining a