Effects of ASR/DEF on Anchorage of Prestressing Strands in Trapezoidal Box Beams with Dapped Ends

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ABSTRACT

Concern about the effects of alkali-silica reaction (ASR) and delayed ettringite formation (DEF) on the shear strength of prestressed concrete trapezoidal box beams with dapped ends prompted an investigation at the University of Texas at Austin. Five dapped-end beams intended for the US 59 corridor project in Houston, Texas were rejected during the casting process due to void rotation and consolidation issues. The beams were stored in the precast yard where they were left exposed for nearly fifteen years. The beams exhibited accelerated ASR/DEF deterioration and represent the potential distress of the in-service trapezoidal box beams.

A review of the literature found that the majority of research with ASR/DEF affected members focused on much smaller, rectangular sections. The unique load transfer mechanisms and reinforcement details within a dapped end rendered the results found in the literature unsuitable for evaluation purposes. The full scale trapezoidal box beams were also distinctive in that no special batching or curing techniques were performed to reproduce the effects of in-situ premature concrete deterioration. The concrete was designed for structural purposes and the beams were not subjected to any acceleration processes other than exposure to the environment.

Load tests were performed to study the effects of ASR/DEF on the primary failure mechanism of the dapped end. The strength of each beam was governed by shear-induced anchorage failure confirmed by the formation of cracks in the development region and audible pops as the prestressing strands slipped. Due to the limited length available for development of the flexural reinforcement, the strength was controlled by the anchorage of the prestressing strand.

Keywords: Alkali-Silica Reaction, Dapped End, Delayed Ettringite Formation, Prestressed Concrete, Research, Shear, Strand Anchorage

INTRODUCTION

Across the State of Texas and many other areas of the world, relatively young concrete structures have developed signs of premature concrete deterioration. In a number of cases, severe surface cracking and occasional spalling have been identified as symptoms of both alkali-silica reaction (ASR) and delayed-ettringite formation (DEF). Uncertainty with regard to the structural effects of the deterioration have led engineers to commonly err on the side of caution; costly repair or replacement schemes have been frequently implemented to eliminate long-term concerns. It is estimated that the Texas Department of Transportation (TxDOT) has more than one billion dollars' worth of prematurely damaged infrastructure in the Houston District alone.[1]

Most of the bridges on the US 59 corridor (between IH 610 and BW 8) and the Katy Central Business District (CBD) HOV lanes were constructed with prestressed trapezoidal concrete box beams. After a little more than a decade in service, many of the exterior box beams are showing signs of premature concrete deterioration.

The Houston District of the Texas Department of Transportation funded a project at The University of Texas at Austin (UT Austin) to conduct structural tests on the dapped ends of the prestressed concrete trapezoidal box beams. In addition, a structural autopsy was to be conducted on one of the heavily cracked beams. Load testing was performed at the Phil M. Ferguson Structural Engineering Laboratory (FSEL) of the University of Texas at Austin.

RESEARCH SIGNIFICANCE

Previous laboratory testing of ASR/DEF-affected reinforced and prestressed concrete beams has not revealed any significant reduction in the flexure or shear strength of simple, well-detailed elements. While the results are generally promising, it is difficult to extrapolate the data to larger, more complex field structures. Load testing has never been performed to investigate the effects of premature concrete deterioration on the structural performance of dapped ends. The majority of research with ASR/DEF affected members focused on much smaller, rectangular sections. The unique load transfer mechanisms and reinforcement details within a dapped end render the test results found in the literature unsuitable for evaluation purposes.

All specimens from literature were also batched with specifically chosen reactive mixtures to reproduce in-situ premature concrete deterioration. Special curing techniques were often used to accelerate the distress in the concrete. The trapezoidal box beams under investigation developed ASR/DEF damage in the normal Houston, Texas climate.

SPECIMEN DESCRIPTIONS

Five trapezoidal box beams were cast for, but not erected within, the US 59 corridor. The beams were rejected during the casting process due to rotation of the Styrofoam void and concrete consolidation issues. Over the past fifteen years, the box beams have been in a precast yard in Houston, Texas. Four of the beams were cast in July 1995 and showed signs of concrete deterioration (ASR and/or DEF) varying from mild to severe. The fifth beam was cast in November 1995 and showed little to no concrete deterioration and can be considered to be representative of an “undamaged” beam. In this paper, the effects of ASR/DEF deterioration on a heavily and lightly cracked beam will be compared.

DIMENSIONS AND REINFORCEMENT LAYOUT

As fabricated, the trapezoidal box beams ranged from 102 to 113 feet in length and weighed between 65 and 71 tons. To facilitate transportation to (and within) Ferguson Structural Engineering Laboratory, each of the box beams was cut into three sections to meet the hauling and laboratory crane limits.

The geometry of the dapped end, solid end block, and hollow void region are illustrated in Fig. 1. The segments contained 62 one-half inch prestressing strands with 24 strands debonded in the end region. The relatively high percentage of debonded strands (39%) coupled with the concentration of the longer debonded lengths at the edges of the beam was expected to have adverse effects on the flexural and shear capacity of the member in the end block region.

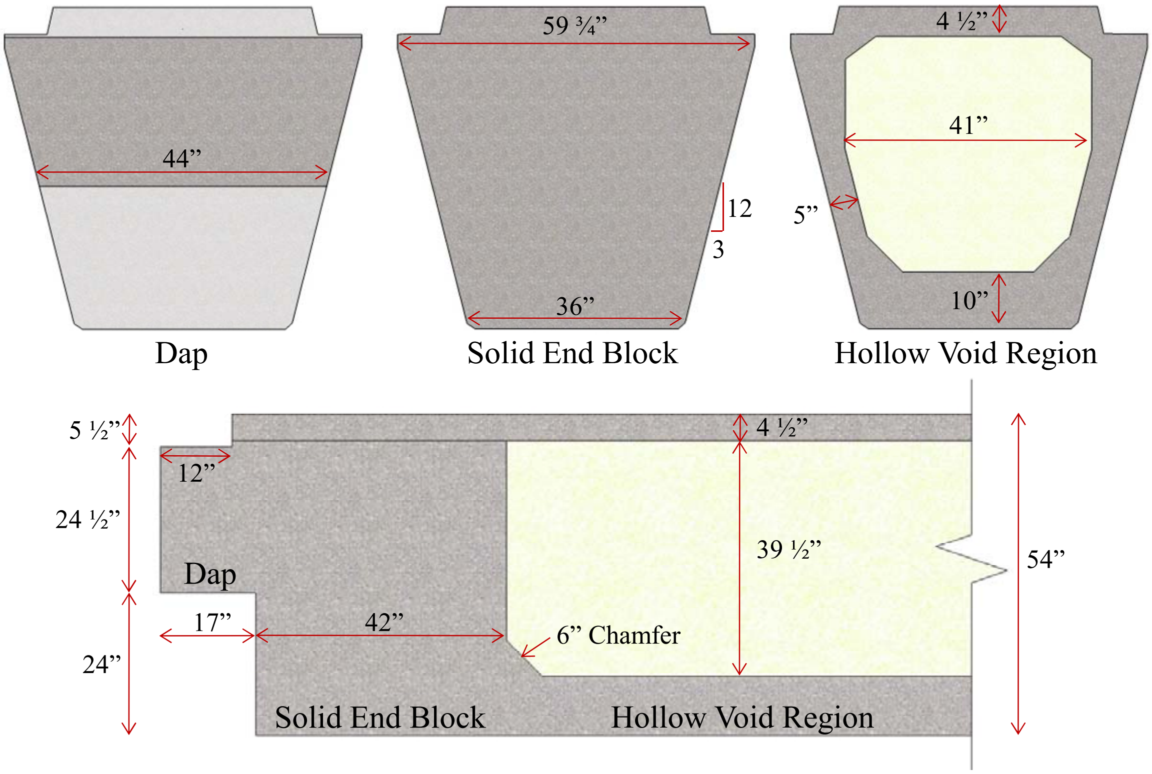
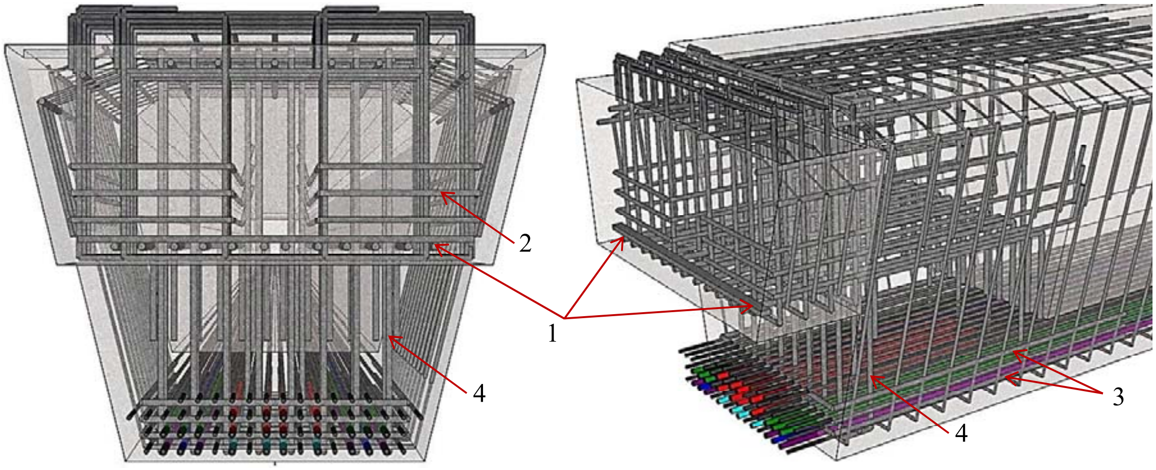


Fig. 1 Dapped End Dimensions of the Trapezoidal Box Beams

The reinforcement layout shown in Fig. 2 was standard for each segment. The original design of the beams was performed following the PCI Design Handbook[2] and the test results indicate that the use of strut-and-tie models are appropriate for designing dapped ends of beams. For a detailed discussion on the STM's used in the analysis of this project please refer to the published thesis on the Ferguson Structural Engineering Lab website.[3]

In order to prevent failure of the dap, the end block of each beam was heavily reinforced. The horizontal dap reinforcement was welded to a plate at the end face and anchored with a 90° hook two inches from the inner face of the end block (1). Additional horizontal hooked bars were provided up to two thirds of the dap height to help prevent cracking at the reentrant corner (2). The large amount of vertical reinforcement located near the reentrant corner (3) was a feature of both strut-and-tie modeling and PCI Design Handbook design methods.[2] This hanger reinforcement extended down through the prestressing strands and, along with three bent bars at the bottom of the beam (4), helped to provide the needed confinement.



End View Isometric View

Fig. 2 Dapped End Reinforcement Configuration

PREMATURE CONCRETE DETERIORATION

The trapezoidal box beams with dapped ends examined in this study were affected by two premature concrete deterioration mechanisms that subjected the concrete to expansive forces, leading to cracking on the surface as shown in Fig. 3. Alkali-silica reactivity (ASR) was first identified as a concrete durability issue in the late 1930's, and significant research has been conducted on it since that time. Delayed ettringite formation (DEF) was first recognized as a potential problem in concrete exposed to high curing temperatures during the early 1980's.

Along with the visual assessment of ASR/DEF-related cracking, findings from a petrographic analysis were used to establish the nature of the deterioration found within the trapezoidal box beam segments. A scanning electron microscope (SEM) and spectral analyses of multiple lapped sections allowed personnel at the TxDOT Concrete Laboratory to identify microscopic features and chemical products of both ASR and DEF present in the beams.[4]

Fig. 3 Visual Effects of ASR/DEF

The surface cracking patterns and visible exterior damage caused by either mechanism are virtually indistinguishable from a structural engineer's perspective. A brief discussion of the chemical and physical properties of the mechanisms will be provided, but no distinction will be made towards their deleterious effects in the rest of this report as both mechanisms were present in the trapezoidal box beams.

(ASR) Alkali-Silica Reaction

ASR results from a combination of high-alkali cement and siliceous aggregates in the concrete mixture. The reactive silica within the course and/or fine aggregates dissolves in the highly basic concrete pore solution and reacts with the alkalis to form a viscous gel. This gel expands as it absorbs water, generating pressure within the aggregates and hardened cement paste. In the presence of sufficient moisture the pressure can easily exceed the tensile strength of the concrete, producing map cracking and/or surface pop-outs.[5]

The expansive capability of the gel is influenced by a number of factors including the reactive aggregate, concentration of alkalis within the pore solution and the availability of sufficient moisture. The reaction is highly responsive to materials, mixture characteristics, and exposure conditions. This sensitivity results in significant variation of deterioration not only between two identical members, but even within a single member.

(DEF) Delayed Ettringite Formation

DEF is a form of sulfate attack that occurs when the concrete is subjected to temperatures in excess of 158°F (70°C) early in the curing process. When fresh concrete is exposed to high temperatures the ettringite decomposes and the sulfates and aluminates become trapped within the early cement hydration products. Over a period of time and with the availability of sufficient moisture, the sulfates and aluminates diffuse out of the hydration products to react and form ettringite. The reformation of ettringite produces expansive forces and micro-cracking of the hardened concrete paste.[5]

The growth of ettringite leads to bulk expansion of the cement paste and the development of cracks and gaps around the aggregates. The ettringite then proceeds to fill the recently formed cracks and create rims surrounding the aggregates, furthering the overall expansion and crack development. The formation of large amounts of ettringite within the hardened cement paste can cause expansions of magnitudes well in excess of those due to ASR and wide variations in cement composition (sulfate content), mixture characteristics (porosity), and exposure conditions will lead to an equivalent variation of deterioration.[5]

SEGMENT CONDITIONS

The cracked surfaces of these beams are assumed to represent the condition of the bridge beams currently in service in 10 to 30 years, depending on environmental exposure conditions and coatings that may be applied to the structures. It is important to appreciate that the deleterious chemical mechanisms ASR and DEF occur at a slower rate in the actual bridge beams due to the protection from the weather provided by the reinforced concrete bridge deck.

The two specimens compared herein are presented in Fig. 4. Varying levels of ASR/DEF-related damage were chosen to determine the effects of cracking on the strength of the dapped ends. The level of distress in each beam, determined by comparing the extent and the width of the cracks, was designated as light and heavy cracking. Widths of the major cracks are shown in Fig. 4 to validate the damage assessment. These cracks ranged from 0.016 inches in the lightly distressed specimen to 0.25 inches in width in the beam that experienced heavy cracking.

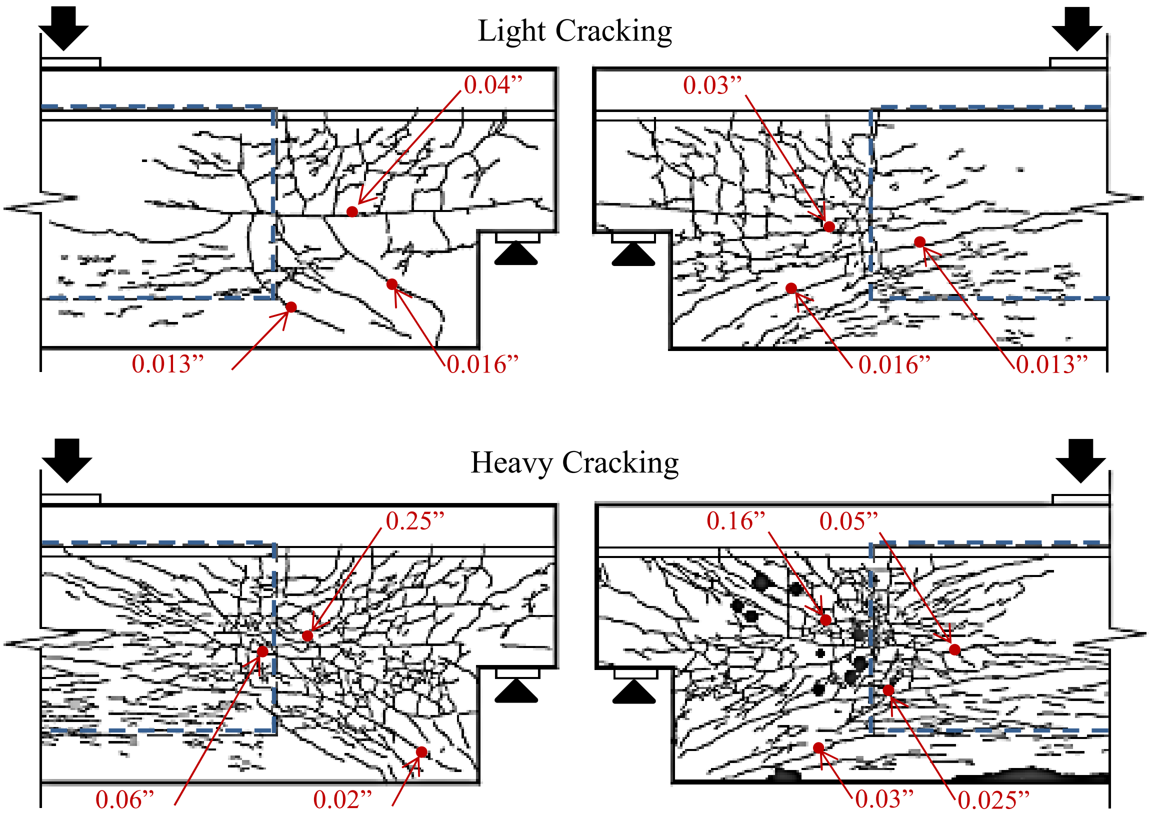


Fig. 4 ASR/DEF- Related Damage to Dapped Ends

BOX BEAM AUTOPSY

A forensic investigation of one of the trapezoidal box beams provided valuable information on the physical effects of ASR/DEF. The box beams were fabricated using standard industry practices and allowed to deteriorate under normal storage conditions. Therefore, the beam provided a unique opportunity to directly inspect the internal damage resulting from nearly 15 years of continuous deterioration. A segment with a standard end block exhibiting heavy deterioration was selected for the structural autopsy. The deterioration was quite severe in comparison to most of the segments. There were wide cracks, small areas of spalling, and efflorescence at some of the cracks.

In order to clearly identify penetration of the surface cracks into the cross-section, the standard end block was injected with epoxy prior to placing the cuts. Once the outer epoxy seal had adequately cured, a black-colored epoxy was injected through carefully placed ports. Sufficient penetration into the crack network was established when a threshold injection pressure was met. The segment was then moved into the lab where cuts perpendicular to the longitudinal axis of the box beam were made with a concrete wire saw.

Contrary to the outward appearance, the surface cracks did not penetrate deep into the structural core of the member. In fact, all of the cracks terminated within ten inches of the beam's surface. The most notable cracks ran parallel to the left side of the cut faces as shown in Fig. 5A. This interior cracking corresponded to the more heavily cracked face of the box beam segment. While the wide parallel cracks occasionally intersected surface cracking, they did not appear to be a direct extension of discrete surface cracks. It is more likely that the internal cracking is the result of the presence of highly localized restraint in the vicinity of the transverse reinforcement and the lack of compatibility between the confined structural core and free concrete surface. While the transverse reinforcement provided confinement to the structural core, the cover concrete was free to expand away from the core.


(A) Severe Cracking Parallel to the Surface (B) Debonding of Reinforcement (C) Fine Inter-Strand Cracking

Fig. 5 Typical ASR/DEF-Related Defects in End Block Cross-Sections

In general, the internal cracks diminished in width and length as the longitudinal distance from the free end of the box beam segment increased. Parallel cracking within the first section (14 inches from the free end) was up to 0.40 inches in width, while the cracks found within the section 55 inches from the free end were a maximum of 0.08 inches in width. The observed trend cannot be attributed to variation of the reinforcement details as the transverse reinforcement was consistently spaced at five inches over the length of the region under consideration. It is likely that the gradient of temperature (and corresponding damage potential) present at the transition from the solid to hollow sections contributed to the diminishing severity of the internal cracking.

The cut face intersected the transverse reinforcement in two of the cross-sections (Fig. 5B). In both cases it appeared as though the cracking led to debonding of the back-side of the transverse reinforcement. The debonded length was relatively short in both cases but could have created a splitting plane through a splice in the vertical bars at that location. Despite the observation, the beams did not exhibit stirrup anchorage failure during testing so it can be assumed that a similar defect in other box beams may not impact overall structural performance.

With regard to the structural effects of the interior damage, fine cracking between the prestressing strands was identified as the most significant aspect of the deterioration. Due to the rapid transfer of prestressing force from the strands to the concrete, tensile (or splitting) stresses were generated in the transverse plane of the beam. While the magnitude of the tensile stress was not great enough to cause splitting cracks, it is likely that it was augmented by tensile stresses related to ASR/DEF actions and resulted in cracking in the horizontal plane of the strands. Close examination (refer to Fig. 5C) of the exposed strand ends revealed fine cracking between a number of strands in each layer. The inter-strand cracking generated by ASR/DEF expansion was suspected to be responsible for the observed loss of anchorage and overall dapped-end capacity that is discussed below

TESTING PROCEDURE

The setup used for the dapped-end testing program is shown in Fig. 6. The beams were simply supported on each end with a single point load applied at a shear span-to-depth ratio of 1.85. The testing frame was composed of a transverse spreader beam attached to two 2,000 kip hydraulic rams each with a 12-inch spherical head to account for slight misalignments. Two 4-inch thick steel plates with dimensions of 26 inches by 24 inches evenly distributed the load to both box beam webs.

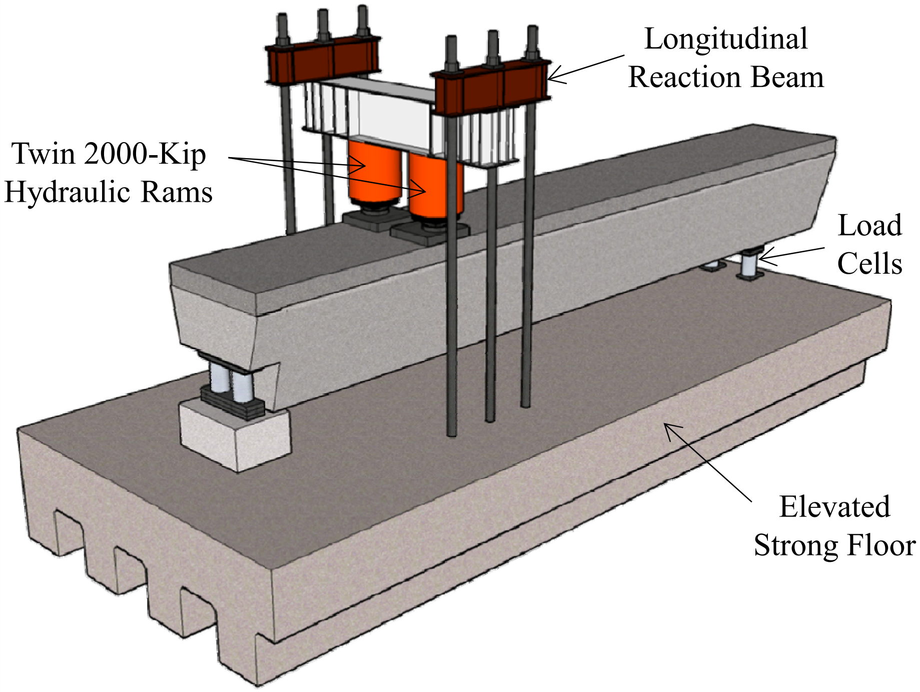


Fig. 6 Test Setup

The ends of each box beam were supported by a total of three bearing plates: one at the dapped end and one under each web at the other end of the beam. The dapped-end bearing plate measured 32 inches by 9 inches and was placed with its long side perpendicular to the longitudinal axis of the beam. The other bearing plates measured 16 inches by 9 inches and were placed under each web parallel to the longitudinal axis of the beam.

Once the segment was positioned in the test setup, a 4-inch topping slab was cast as would have been the case in the field. The ASR/DEF-related surface cracking was marked and thoroughly documented through photographs and crack width measurements. Load increments of 100 kips (total load) were applied until the first new crack was observed. The increments were then decreased to 50 and 25 kips in order to carefully observe the crack progression and accurately record critical loads. Once the shear crack widths exceeded 0.06 inches load was steadily increased to failure.

RESULTS AND DISCUSSION

One of the major concerns with the prestressed concrete trapezoidal beams was the capacity of the extended portion (dap). This smaller section had less concrete to resist the heavy shears in the ends of beams and concerns were raised that it would govern the strength of the beam. Through load testing it was found that the strength of the smaller section did not control and it was concluded that a “dap failure” was not likely for the specimens in this study due to the presence of heavy reinforcement in the extended portion of the beam. The governing aspect of the dapped-end design used in the US 59 trapezoidal box beams was discovered to be the anchorage of the mild and prestressed flexural reinforcement.

Loading of the lightly and heavily cracked beams at a shear span-to-depth ratio of 1.85 resulted in shear-induced anchorage failures. In general, diagonal cracks (preexisting and load-induced) extended into and opened within the transfer length of the prestressing strands as shown in Fig. 7A. The cracks have been highlighted for the benefit of photographs and identifying the formation of new shear cracks during testing. Subsequent extension of the diagonal cracks across the bottom side of the box beam (Fig. 7B) was accompanied by minor spalling in several of the beams. A loud pop signified significant slip of the prestressing strands and a drastic loss of load-carrying capacity. In most cases, the shear-induced anchorage failure was accompanied with the extension of pre-existing ASR/DEF cracks.

The heavily cracked segment produced the most sudden, pronounced failure of the damaged dapped ends (shown in Fig. 7C). Pre-existing ASR/DEF cracks connected between the load and bottom corner of the beam, forming a large, continuous crack that widened extensively and extended into the deck under the hydraulic rams and under the beam in the strand anchorage area. The maximum applied shear resisted was 659 kips. The lightly damaged segment failed at 711 kips.


(A) Cracking in Transfer Length (B) Bottom-Side Anchorage Cracks


(C) Post-Failure Widening and Extension of ASR/DEF Cracks

Fig. 7 Typical Features of ASR/DEF Damaged Segment Failure

As shown in Fig. 8, the linear-elastic response extended to 70 or 80 percent of the maximum applied shear. After that level, the stiffness reduced as a result of preexisting crack growth and new crack development. The most significant aspect of the load-deflection plot of the distressed dapped ends is the higher stiffness of the more damaged beam.

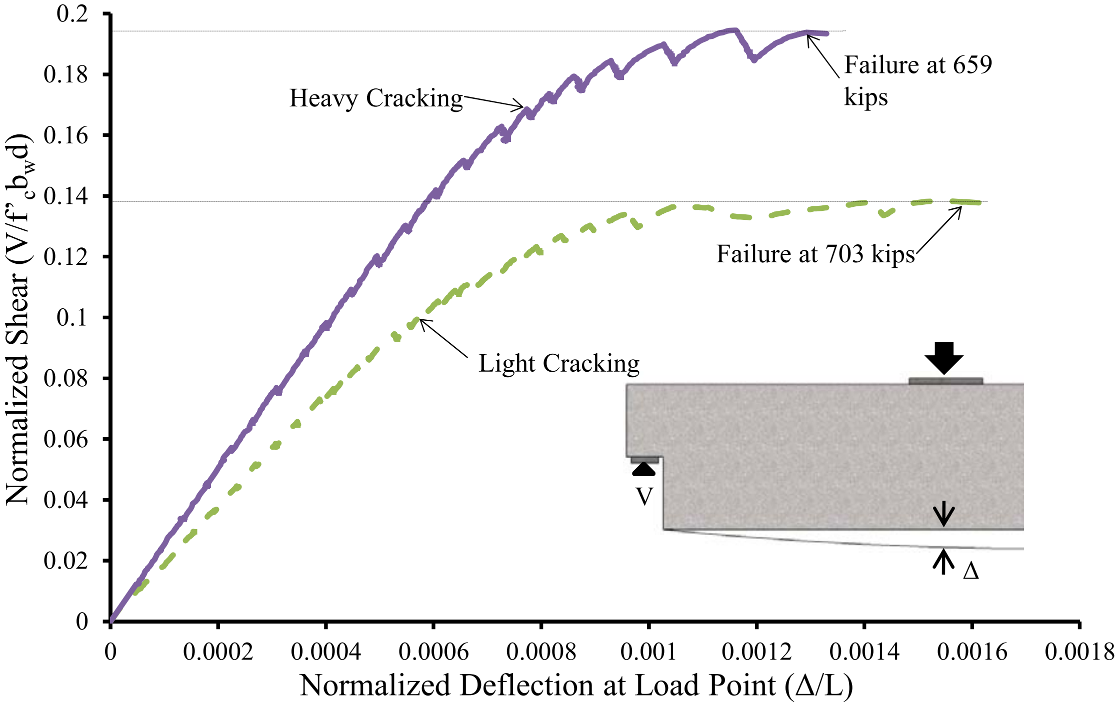


Fig. 8 Load-Deflection Responses (Normalized Shear Stress)

It is likely that restraint of the ASR/DEF-related expansions by the dapped-end reinforcement led to the development of compression within the structural core concrete; eliciting a stiffer material response. Cores were used to estimate the concrete strength in each beam and it was found that the heavily cracked beam had a lower compressive strength than the lightly cracked beam. ASR/DEF-induced compression has been shown to be capable of offsetting (and superseding) the loss of mechanical strength or stiffness due to the microstructural cracking.[6]

The presence of ASR/DEF-induced compression also provided a logical explanation for the observed delay of first cracking in the damaged segments. The development of load-induced cracking in the light and heavily damaged segments is shown in Fig. 9. The illustrations cover the full range of behavior noted during the tests. The response of the segment with light cracking was similar to an undamaged segment. First cracking was noted to occur at a relatively high percentage of the capacity (67 percent), but an extensive crack network was nonetheless present prior to failure. The behavior of the heavily cracked beam (subject to 0.25-inch wide cracks) was drastically different. Significant shear cracking did not develop at any point in the dapped-end test, including failure.

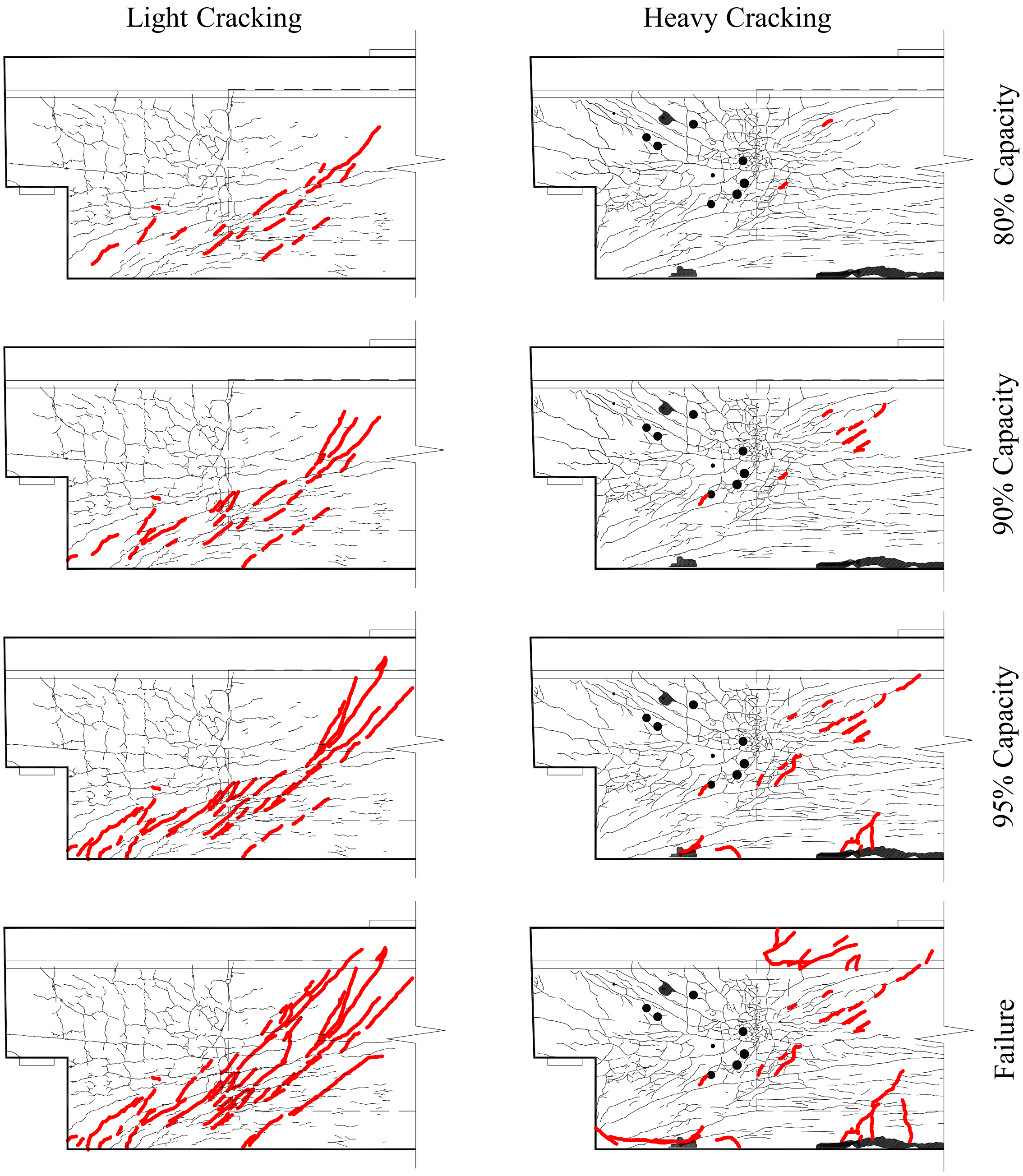


Fig. 9 Diagonal Cracking on the West Faces of Segments L-II and H-II

The only notable crack on either face of the heavily damaged segment (shown in Fig. 7C) corresponded to a preexisting ASR/DEF crack. Overall, the results suggest that either greater ASR/DEF-related damage led to the development of higher internal compressive stresses which further delayed the formation of load-induced cracking or that there was no need for more cracks to form as extensive cracking already existed. Briefly stated, the serviceability characteristics of the damaged dapped ends generally supported the assertion that the expansion-induced compressive stresses within an ASR/DEF-affected member can effectively offset (and potentially negate) the structural effects of reduced strength and stiffness in plain concrete.[6]

Historically the considerable loss of elastic modulus and tensile strength in plain concrete has led to concerns regarding the strength of distressed concrete structures. A review of simple beam tests conducted over the last three decades revealed that the ASR/DEF deterioration did not lead to a measureable loss of strength or stiffness in flexure or shear.[6]

The anchorage of mild reinforcement and prestressing strand, however, does not benefit from the ASR/DEF-induced compression. Many of the strands in the trapezoidal box beams are located away from the transverse ties. The concrete expansion mobilizes the ties but does not help to reduce cracking between the strands or the loss of cover through spalling. At a certain point, it appears that the pre-existing cracking in the development and transfer region can negate any benefit gained from the expansion of the concrete. Application of load increases the size and extent of the cracks, further undermining the bond between the concrete and steel, resulting in anchorage failure.

The shear strength of the heavily damaged beam was relatively unaffected despite the large cracks in the end block. What is important to note is that these beams failed due to shear induced anchorage failure. It was not the strength of the concrete, but the anchorage of the prestressing strands that controlled the failure of both beams. Based on the preliminary analysis of the results, it appeared that premature concrete deterioration slightly weakened the anchorage of the flexural reinforcement in the dapped-end region. The lightly damaged segment supported a higher shear (703 kips) than the heavily cracked beam which could only withstand 659 kips.

The failure mode of the beams highlights the critical nature of the confinement provided by well-anchored reinforcement in ASR/DEF-affected structures. Loss of the confinement (perhaps through rebar fracture[7]) would lead to severe implications for the integrity of damaged structures. The results suggest a loss in strength through anchorage failure with increasing deterioration. The difference between these two beams is relatively small, only a little greater than 6%, but the lightly cracked beam has most likely already suffered a reduction in anchorage capacity. Any additional ASR/DEF distress beyond the “heavily cracked” specimen could quite possibly result in values below dapped-end design capacity.

CONCLUSIONS AND RECOMMENDATIONS

The observations and data gathered over the course of the study provide a clear picture of the relationship between the severity of the ASR/DEF deterioration and the structural performance of the dapped-end beams. The most important aspects of that relationship are summarized below.

The results of the tests are in agreement with the findings of previous projects. The flexural and shear capacity of the trapezoidal box beams were not greatly affected by the ASR/DEF deterioration. However, the structural capacity of the dapped ends was governed by shear-induced anchorage failure. The initial attempt to fail the dap (partial depth portion) in shear resulted in anchorage failure of the prestressing strands. Detailed review of the beam design revealed the critical nature of the flexural reinforcement anchorage. Due to the relatively short length available for prestressing strand development, this detail will likely control failure of the beam end irrespective of the shear span-to-depth ratio.

Two particular characteristics of the damage suggested that ongoing ASR/DEF deterioration was responsible for the loss of anchorage capacity. First, relatively large surface cracks (up to 0.03 inches wide) were identified within the prestress transfer region of all the deteriorated segments. Second, structural autopsy of one box beam segment revealed fine cracks between the prestressing strands.

The results of the tests provide immediate insight to the severity of the problem that exists in most of the bridges within the US 59 corridor and the Katy Central Business District HOV lanes in Houston, Texas. Careful review of the project's findings will enable TxDOT engineers to make better repair/replacement recommendations for the trapezoidal box beam bridges as well as other structures in which ASR/DEF related cracking is evident within the State of Texas.

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