Precast-Prestressed Concrete Bridge Girders Damaged by Over-Height Load Impacts

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ABSTRACT

Over-height loads that impact bridges cause damage and service interruptions. The resulting damage to precast-prestressed bridge girders ranges from minor cracks and spalls to complete loss of structural integrity. Case studies of recent over-height load impacts in Washington State are discussed including damage assessment, method of repair, and repair costs. Washington State Department of Transportation design criteria for improving impact resistance and repair and replacement guidelines are also presented.

Keywords: Girders, Impact, Damage, Repair

INTRODUCTION

Impact by over height loads is a common source of damage to precast prestressed girder bridges. Damage can range from minor spalling and cracking to complete loss of structural integrity. Examples of over height load impact events occurring in Washington State are presented including damage assessment, method of repair, and, when available, repair costs. Washington State Department of Transportation (WSDOT) design criteria for improving impact resistance and guidelines for repair and replacement are also presented.

CASE STUDIES OF HIGH LOAD IMPACT EVENTS

A variety of high load impact events in Washington State are described in the following case studies. The bridge configurations include single span structures, simple span structures, and continuous structures. Cases of minor, moderate, and severe damage are described.

Insofar as the information is available these case studies describe the nature of the impact event, the damage assessment, the repair method, and the cost of the repair project. The cost figures reported are for the total cost of the repair project which includes mobilization, traffic control, removal of damaged bridge elements if necessary, and all structural repairs and other incidental construction related activities.

STATE ROUTE 3 - TRIGGER AVENUE UNDERCROSSING

The Trigger Avenue structure crossing State Route 3 near Bremerton, Washington was hit by an excavator being hauled by semi-tractor with a low boy trailer. This event occurred on June 3, 2002. The structure is a two span continuous precast-prestressed girder bridge and is shown in Figure 1. The impact occurred where the downhill grade of SR 3 crosses beneath the structure. The clearance between the roadway and the structure is 16’-3”.

Figure 1 Trigger Avenue Bridge over State Route 3

Damage to the structure was minimal. A patch of concrete cover on the bottom flange of the girder, directly adjacent to an unused sign support bracket, was spalled off at the point of impact. The damaged area was approximately 3 feet in length. Several strands were exposed, however none were damaged. The location of impact and subsequent damage is shown in Figure 2.

Figure 2 Impact site and damage to the Trigger Avenue structure

Repair of the girder was complicated by the sign structure support bracket. The bracket was permanently removed to simplify the repair. The structure was repaired by chipping away all loose concrete, forming the bottom flange, and patching with a concrete patching and repair mortar. Repairs were conducted by WSDOT maintenance personnel.

STATE ROUTE 14 - LIESER ROAD BRIDGE

The Lieser Road Bridge crosses State Route 14 near Vancouver, Washington. This structure, shown in Figure 3, is a two span continuous precast-prestressed girder bridge. The minimum vertical clearance is 16.0 ft.


Figure 3 Lieser Road Bridge

This bridge has endured several impact events during its service life. The most serious event took place on November 21, 2005. Seven of the eight girders in the bridge cross section suffered damage. The exterior girder that sustained the direct impact and the adjacent interior girder suffered the most damage. There was severe spalling and missing concrete over a distance of 40 ft in the web and bottom flange. Each of these two girders had sixteen exposed prestressing strands. Five of the strands in the bottom row of reinforcement were completely severed and two additional strands had broken wires. Harped strands were exposed by the damage. The stirrups were bent and permanently deformed. Minor spalling at the end of the girder connecting to the intermediate pier diaphragm was also noted. The five other damaged girders suffered minor spalling and concrete damage in the bottom flange. Photographs of the damage were not available.

The five girders with minor damage were repaired by WSDOT maintenance personnel. Repairs consisted of chipping away all loose concrete, forming the bottom flange, and patching with a concrete patching and repair mortar. The two girders with severe damage were replaced under contract. The bridge deck, railing system, and continuity diaphragms were carefully removed to facilitate the removal and replacement of the damaged girders. New girders were fabricated and installed. The diaphragms, deck, and railing were replaced to complete the repair. The total cost of repairs under this contract was $623,000. This equates to a cost of $6,184 per foot of girder.

A similar impact event occurred on February 4, 2008. A dump truck hauling an excavator traveling eastbound on SR 14 hit three girders. The exterior girder had a single impact spall and four severed strands in the bottom flange. There was a 40 ft long hairline crack at the interface between the top flange and the web directly above the point of impact. The bottom flange was laterally displaced 3/8” at the impact location. The next three interior girders were not damaged suggesting that the load was compressed or rotated from the initial impact and then rebounded to impact two interior girders. The second girder hit had one impact spall and two exposed strands. One of the strands had two wires that were severed and a third that was nicked. The third girder hit had minor spalling.

All of the girders were deemed repairable. Loose concrete was removed from the damaged areas. Additional concrete was removed around the severed strands to facilitate the repair. Severed strands were joined and tensioned with a splice coupler system shown in Figure 4. The damaged areas were formed and the concrete was repaired with a patching and repair mortar. Repairs were carried out by WSDOT maintenance personnel.

Figure 4 Repair of severed strands with coupling device

INTERSTATE 90 - EASTON ROAD BRIDGE

The Easton Road Bridge over eastbound I-90 near Easton, Washington was damaged by an over-height load on October 31, 2007. The structure is comprised of five simply supported spans of precast-prestressed concrete girders. The minimum vertical clearance for this structure is 17.0 ft. The over-height load, shown in Figure 5, was a support column for a wind turbine structure.


Figure 5 Over-height load that damaged the Easton Road Bridge

The impact caused a complete loss of structural integrity in one span of the bridge. The bottom flange and web of all six of the girders in the cross section were damaged beyond repair. The damaged structure is shown in Figure 6. The collision forced the closure of the I-90 eastbound lanes and traffic was detoured onto the Easton interchange ramps. WSDOT crews and an emergency contractor demolished the damaged bridge span and re-opened the eastbound lanes of I-90 within 24 hours of the collision. Secretary of Transportation Paula Hammond challenged WSDOT engineers to “get creative – get this bridge replaced as quickly and effectively as possible.” WSDOT met the challenge and opened the structure in 45 days.


Figure 6 Damage to the Easton Road Bridge

This structure is located in a mountain pass and winter weather conditions are common in late fall. Placement of concrete in cold weather conditions was a major concern. WSDOT designers selected decked bulb tee girders rather than in-kind replacement of I-girders with cast-in-place deck. This eliminated a substantial quantity of cast-in-place concrete and accelerated the construction of the replacement span. With the availability of high performance concrete and 0.6” diameter prestressing strands, five precast-prestressed decked bulb tee girders replaced the six original I-shaped girders. The total cost of the replacement contract was $703,000. This equates to a cost of $2,379 per foot of girder.

In addition to challenges posed by freezing temperatures and snow storms, the section of I-90 impacted by this project was experiencing unusually high traffic demands. Flood induced closures of I-5 nearly 140 miles away in Chehalis, Washington forced southbound traffic from Seattle to travel east on I-90 to an alternative southbound route towards Portland, Oregon. Construction activities were halted when excessively long traffic backups occurred.

INTERSTATE 5 - CHUCKANUT DRIVE OVERCROSSING

A truck towing an excavator on northbound I-5 hit and severely damaged the Chuckanut Drive overpass in Burlington, Washington on July 10, 2008. This structure is a four span precast-prestressed girder bridge. The minimum vertical clearance of the structure is 15'-5". The Washington State Patrol reported the height of the load to be 17 ft. Routine inspection reports note scrapes on the bottom flanges of the girders as well as patching from previous impact events.

The cross section of the bridge consists of six simple span precast-prestressed girders with a cast-in-place composite concrete deck. Three girders were damaged by this impact event. The exterior girder taking the initial impact, shown in Figure 7, suffered severe spalling of the bottom flange and web concrete. Twenty stands were exposed and eleven were severed. The harped strands were fully exposed at the harp point. The concrete confining the harped strands was damaged resulting in a change of strand geometry and loss of prestress force. The next three girders in the cross section were undamaged suggesting that the load was compressed or rotated due to the initial impact and then rebounded as it moved beneath the structure.

Figure 7 Damage to girder receiving direct impact

The second girder damaged was the first interior girder on the opposite side of the structure relative to the point of initial impact. The damage to this girder was nearly identical to the girder experiencing the initial impact. There was significant cracking and spalling of the bottom flange and web concrete. Twenty strands were exposed and eleven were severed. The harped strands were partially exposed. The third girder hit was adjacent to the second damaged girder and was the exterior girder on the far side of the structure. The damage to this girder was much less severe. There was moderate concrete spalling and eight prestressing strands were exposed. The impact damage to the second and third girders is shown in Figure 8.


Figure 8 Damage to second and third girders

Truck traffic was removed from the structure and car traffic was reduced to one alternating lane of traffic over the three undamaged girders. Temporary repairs were made by WSDOT maintenance personnel. The repairs consisted of splicing and re-tensioning the severed strands, shown in Figure 9, to restore some of the load carrying capacity to the girders. Due to space constraints, only seven of the eleven severed strands could be spliced. The structure was returned to its original two lane configuration though gross vehicle weight was restricted to 80,000 lbs. Ultimately WSDOT secured federal emergency funds to repair the structure. The damaged span was removed and replaced. The total cost of the span replacement project was $723,000. This equates to a cost of $2,939 per foot of girder.

Figure 9 Temporary repairs using strand couplers

INTERSTATE 5 - SOUTH 178TH STREET BRIDGE

A tractor hauling a high load transformer on a low boy trailer struck and damaged the South 178th Street Bridge crossing I-5 near Tukwila, Washington on December 13, 2006. The structure is a typical highway overcrossing with four simply supported precast-prestressed girder spans. The vehicle had a valid permit and was instructed to travel in the right hand lanes for adequate clearance. The load was traveling in the left hand lanes as it ascended the grade beneath the structure. The load collided with the exterior girder on the far side of the structure.

The impacted girder suffered cracks and spalls to the bottom flange and web concrete over the majority of the length of the girder. The damage in the web extended to the interface with the top flange of the girder as seen in Figure 10. Several strands were exposed and three were severed. The bottom flange was displaced 4” laterally at the point of impact.

Figure 10 Damage to the South 178th Street Bridge

Loose material was removed from the damaged girder. South 178th street was reduced to one alternating lane of traffic.

This structure was repaired by removing the affected railing, deck, and damaged girder and replacing these components in-kind. Repairs were carried out under contract at a total cost of $895,000. This equates to a cost of $8,861 per foot of girder.

INTERSTATE 5 - 113TH AVENUE BRIDGE

On March 22, 2011 a truck hauling a fork lift on a flatbed trailer struck and damaged the 113th Avenue Bridge over I-5 near Tumwater, Washington. The structure is a typical highway overcrossing with four simply supported precast-prestressed girder spans. The minimum vertical clearance is 16’-6”.

A single girder was damaged by this impact. The mast was torn from the forklift preventing damage to other girders as it moved beneath the structure. The bottom flange and web suffered severe cracking and spalling. Fourteen strands were exposed, two strands were severed and one strand was nicked. A section of the web and bottom flange was knocked out at the point of impact. Epoxy sealed web cracks from previous impacts were widened due to the impact of this event. The bottom flange was permanently displaced ½” laterally.

Figure 11 Girder damage on the 113th Avenue Bridge

The bridge cross section consists of four precast-prestressed girders spaced at 8.0 ft. The east bound lane of 113th Avenue was closed to traffic due to the location of the damaged girder below the south lane, the lack of redundancy in the damaged span, and quantity of heavy truck traffic due to a nearby gravel/concrete operation.

This structure was repaired by removing the affected railing, deck, and damaged girder and replacing these components in-kind. Repairs were carried out under contract with a Preliminary Engineering cost of $109,639, a Construction Engineering cost of $106,815 and a construction cost of $272,065. The total cost was $488,519. This equates to a cost of $8,246 per foot of girder.

STATE ROUTE 16 - OLYMPIC ROAD BRIDGE

The Olympic Road Bridge was struck by the mast of a forklift carried on a lowboy trailer which was travelling northbound on State Route 16 near Gig Harbor, Washington on January 4, 2011. This is a two span continuous precast-prestressed girder bridge structure. The load impacted the last girder as it travelled along an ascending grade beneath the bridge. The minimum vertical clearance is 15’-8”.

The mast impacted the girder causing numerous fractures including bottom flange and web spalls exposing twenty six prestressing strands, two longitudinal mild steel reinforcing bars, and eight stirrups. The exposed stirrups were permanently deformed. Spalling also occurred away from the point of impact at the interface of the girder and the pier cap at the center pier. This spall exposed one prestressing strand and three mild steel reinforcing bars. There was also longitudinal web splitting cracks along the top flange for most of the girder length, several elliptical web cracks around the point of impact, and a few longitudinal cracks along the bottom flange. No prestressing strands were severed. The concrete diaphragm connection at the 1/3 point of the girder sustained a prying force creating cracks and shallow spalls in the girder web adjacent to the diaphragm. These web cracks extend and join the longitudinal crack at the top flange/web interface. Damage to the exterior face of the girder opposite the point of impact and at the center pier is seen in Figure 12.

Figure 12 Olympic Road Bridge Girder Damage

The damage to the girder was too extensive to repair. The affected railing, deck, and damaged girder were removed and replaced in-kind. Repairs were carried out under contract with a Preliminary Engineering cost of $132,286, a Construction Engineering cost of $177,232 and a construction cost of $541,800. The total cost was $851,318. This equates to a cost of $8,643 per foot of girder.

A similar impact event occurred March 17, 2013. A semi-tractor with a low boy trailer hauling an asphalt burner hit the girder that was replaced due to the 2011 event. The resulting damage in this event was more severe than the previous event. There were large spalls and cracking in the bottom flange and webs at the point of impact. Twenty six strands were exposed and five strands were severed. The bottom flange was permanently displaced 3" laterally at the point of impact. Several stirrups had permanent deformation or were pulled free from the concrete. Prying forces were developed at the 1/3 point intermediate diaphragm causing cracking and spalling of the web concrete. There was a 1½" separation between the web and diaphragm. The end of the girder was laterally displaced 3/16" at its interface with the center pier diaphragm. Damage at the point of impact is seen in Figure 13 and lateral displacement of the girder at the center pier is seen in Figure 14.

Figure 13 Olympic Road Bridge girder damage at point of impact

Figure 14 Lateral displacement of girder at center pier diaphragm

The damage to the girder was too extensive to repair. The affected railing, deck, and damaged girder will need to be removed and replaced in-kind similar to the repairs for the 2011 impact event.

STATE ROUTE 167 - 24TH STREET BRIDGE

On December 15, 2009 the 24th Street Bridge over State Route 167 near Sumner, Washington was hit. A tanker truck traveling at a high rate of speed veered off the road, climbed an embankment and impacted the structure. This structure is a three span continuous precast-prestressed girder bridge.

The impact damaged the exterior girder in several locations as seen in Figure 15. At the east abutment, the bottom flange had spalled off the girder resulting in a loss of bearing. Six prestressing strands were exposed and were clearly no longer tensioned.

At the point of impact the bottom flange had considerable spalling with exposed prestressing strands. Several of the strands could be moved by hand indicating a loss of prestress. Stirrups were exposed, bent, and broken. The bottom flange was permanently displaced 3-1/4" laterally.

Cracking and spalling occurred at the continuity diaphragm on the west end of the span.

Figure 15 Impact damage to the 24th Street Bridge

The damage to the girder was too extensive to repair. The affected railing, deck, and damaged girder were removed and replaced in-kind. Repairs were carried out under contract with a Preliminary Engineering cost of $250,952, a Construction Engineering cost of $204,614 and a construction cost of $658,225. The total cost was $1,113,791. This equates to a cost of $8,328 per foot of girder.

CASE STUDY SUMMARY

Several examples of precast-prestressed concrete girder bridges damaged by over-height load impacts have been presented. Table 1 summarizes the cost of repairs for simple span and continuous span structures.

Span Type	**Repair Type**	**Year**	**Cost**	**Linear Feet of Girder Replaced**	**Cost/ft**
Continuous	Girder replacement	2005	$623,000	100.8	$6,184
Simple	Span replacement (5 girders)	2007	$703,000	295.5	$2,379
Simple	Span replacement (4 girders)	2008	$723,000	246.0	$2,939
Simple	Girder replacement	2006	$895,000	101.0	$8,861

Simple	Girder replacement	2011	$489,000	59.3	$8,246
Continuous	Girder replacement	2012	$851,318	98.3	$8,643
Continuous	Girder replacement	2012	$1,114,000	133.8	$8,328

Table 1 Case Study Summary

DESIGN CRITERIA AND GUIDELINES

WSDOT has recently added criteria to its Bridge Design Manual[1] (BDM) for improving the impact resistance of newly designed bridges, repair design guidelines for girders damaged by vehicular load impacts, and criteria for assessing repair versus replacement options for impact damaged prestressed concrete bridge girders.

GUIDELINES FOR IMPROVING IMPACT RESISTANCE

WSDOT sponsored a research project[2] to learn the effect of intermediate diaphragms on the performance of precast-prestressed concrete I-girders, wide flange girders, and deck bulb tee girders during high-load impact events. The research investigated the location of intermediate diaphragms within a span, the size of intermediate diaphragms (width and depth), girder spacing, girder depth, aspect ratio (ratio of span length to deck width), and the impact load contact interface (concentrated and distributed loading). The research concluded that the two most significant factors for improving impact resistance through design were the location and depth of intermediate diaphragms. Multiple distributed intermediate diaphragms better dissipate energy, provide a load path for load sharing between multiple structural members and reduce overall damage to precast prestressed concrete bridge girders. Shallow intermediate diaphragms (partial depth diaphragms) were found to be quite detrimental to the girders and intermediate diaphragms that extend to the top edge of the bottom flange (full depth diaphragms) permit less rotation of the girder and better impact protection to the bridge system.

Based on this research, WSDOT has adopted the following criteria for the number and depth of intermediate diaphragms used in precast-prestressed girder bridges with I-shape, wide flange, and deck bulb tee type girders.

- Location of Intermediate Diaphragms
    - 1/5 points of span for span lengths greater than 160 ft
    - 1/4 points of span for 120 ft < span length ≤ 160 ft
    - 1/3 points of span for 80 ft < span length ≤ 120 ft
    - Mid-point of span for 40 ft < span length ≤ 80 ft
    - No diaphragms required for span length ≤ 40 ft
- Depth of Intermediate Diaphragms
    - Full depth intermediate diaphragms shall be used for bridge crossings over roadways with ADT greater than 50,000.
    - Full or partial depth intermediate diaphragms shall be used in for all other cases. In making the determination of diaphragm depth relevant factors should be taking into consideration including minimum vertical clearance, previous

impact events in the vicinity of the structure, and unusual frequency of over height loads.

REPAIR DESIGN

The determination of the degree of damage to a precast prestressed concrete bridge girder is largely a matter of judgment. Where section loss has occurred or prestressing strands have been severed, calculations can aid in making this decision. The WSDOT BDM presents general categories of damage and suggested repair procedures.

Minor Damage

If the damage is slight and concerns only spalling of small areas of the outside surface of the concrete, repair may be accomplished by replacing damaged concrete areas with concrete grout. The area where new concrete is to be applied shall first be thoroughly cleaned of loose material, dried, and then coated with epoxy.

Moderate Damage

If damage is moderate, consisting of substantial section loss and possibly loss of one or more strands, a suitable repair procedure must be developed. It is probable that some prestress will have been lost in the damaged area due to severed/damaged strands and a reduction in section stiffness and consequently strand shortening. The objective of the recommended repair procedure is to assure that as much of the original girder strength as possible is retained.

WSDOT's recommended repair procedure is as follows:

1) **Determine Condition** – Sketch the damaged cross section of the girder and compute its reduced section properties. Determine the stress in the damaged girder due to the remaining prestress and loads in the damaged state. If severe overstresses are found, action must be taken to restrict loads on the structure until the repair has been completed. Consideration should be given to replacing the girder if the loss of prestress is so great that the prestressing requirements defined in the AASHTO LRFD Bridge Design Specifications[3] cannot be satisfied.
2) **Restoration of Prestress** – Calculations must be performed to determine the preloading required to restore the girder to its original state of stresses[4,5]. Determine the original design stress in the bottom fiber of the girder due to dead load, live load, dynamic load allowance, and prestress. Determine the location and magnitude of a preload force that, when applied to the damaged girder, will result in the same stress in the bottom fiber as the original design stress. Take into account the reduced girder section, the effective composite section, and any reduced prestress due to strand loss. The preload will elongate and tension the prestressing strands. After the concrete section is repaired, removal of the preload will cause the girder to deflect upwards introducing compression into the bottom flange. When the damage occurs outside the middle one-third of the span length, the shear stress due to the preload should be

taken into account. When strands have been severed, consideration should be given to coupling and tensioning them to restore their prestress.

3) **Prepare a Repair Plan** – The repair plans shall indicate how the preload is to be applied and how the concrete section is to be repaired. Specify that the preload is to remain in place until the grout has obtained sufficient strength. Specify that the damaged area is to be thoroughly prepared, coated with epoxy, and repaired with grout equal in strength to the original concrete.
4) **Test Load** – When there is reason to believe that the girder strength could not fully be restored, consideration should be given to testing the repaired girder with a load equivalent to $1.0DL + 1.5(LL+IM)$ where DL is the in-situ dead load and $LL+IM$ is the design live load plus dynamic load allowance.

Severe Damage

When the damage to the girder is considered to be irreparable due to extreme cracking, considerable loss of prestressing, excessive permanent lateral deformation of the bottom flange, loss of structural integrity, or other such conditions, the girder or perhaps the entire span, must be replaced. In general, the replacement procedure consists of carefully cutting through and removing the deck slab, diaphragms, and railing system to permit removal of the damaged girder. An adequate amount of reinforcing steel must be preserved to allow splicing and development of new reinforcement. The new girder and reinforcement are placed. The cut concrete surfaces are cleaned and coated with epoxy. The deck slab, diaphragms, and railing system are reconstructed. Intermediate diaphragms adjacent to exterior girders are replaced with full depth diaphragms. Replacement girders should be the same type as the original girder.

It is important that the camber of the replacement girder be matched with that of the existing girders. Excessive camber in the replacement girder can result in inadequate deck slab thickness. Girder camber can be controlled by the arrangement of prestressing, the use of temporary top strands, and curing time. Excessive camber can be accommodated to a degree with dimensional changes from the original girder or the bearing seat elevation.

If necessary, the deck slab and diaphragms can be cast simultaneously to avoid overloading the existing girders in the structure. Lateral bracing of the girder at the time of deck slab pour is required.

The method of construction specified in the plans must minimize inconvenience and dangers to the public while achieving a satisfactory structural result. High early strength grouts and concrete should be considered.

REPAIR VERSUS REPLACEMENT

Several factors are considered when evaluating whether to repair or to replace a damaged prestressed girder. These include the level of concrete damage, number of broken strands, location and magnitude of web damage, permanent offset of the original girder alignment, and overall structural integrity. Other considerations include cumulative damage due to previous impact events, damage to adjacent girders, and cost of repair versus replacement. Ultimately, the evaluation hinges on whether the girder can be restored to its original capacity and whether the girder can be repaired sufficiently to carry its share of the design load.

The following guidelines describe damaged girder conditions which require replacement:

- ***Strand Damage*****:** More than 25% of prestressing strands are damaged/severed.
  When more than 25% of the strands have been severed, replacement is required. Splicing is routinely done to repair severed strands. However, there are practical limits as to the number of couplers that can be installed in the damaged area.

- ***Girder Displacements****:* The bottom flange is laterally displaced more than ½" per 10' of girder length.
  When the alignment of the girder is permanently altered by the impact, replacement is required. Examples of non-repairable girder displacement include cracks at the web/flange interface that remain open. Abrupt lateral offsets indicate that stirrups have likely yielded. A girder that is permanently offset may not be restorable to its original geometric tolerance by practical and cost-effective means.

- ***Concrete Damage at Harping Point****:* Concrete damage at harping point resulting in permanent loss of prestress.
  Extreme cracking or major loss of concrete near the harping point may indicate a change in strand geometry and loss in prestress force. Such loss of prestress force in the existing damaged girder cannot be restored by practical and cost-effective means, and requires girder replacement.

- ***Concrete Damage at Girder Ends:*** Severe concrete damage at girder ends resulting in permanent loss of prestress.
  Extreme cracking or major loss of concrete near the end of a girder may indicate unbonding of strands and loss in prestress force. Such loss of prestress force cannot be restored by practical and cost-effective means, and requires girder replacement.

There are other situations as listed below which do not automatically trigger replacement, but require further consideration and analysis.

- ***Adjacent Girders*****:** Capacity of adjacent undamaged girders.
  Consideration must be given as to whether dead load from the damaged girder has been shed to the adjacent girders and whether the adjacent girders can accommodate the additional load.

- ***Damaged Adjacent Girders:*** Damage to adjacent girders.

Replacement may also be warranted if the adjacent girders have been damaged from this or previous impact and have reduced capacity.

- ***Previously Damaged Girders****:* Damage to a previously damaged girder.
  An impact to a girder that has been previously damaged and repaired may not be able to be restored to sufficient capacity.

- ***Cost:*** Cost of repair versus replacement.
  Replacement may be warranted if the cost of repair reaches 70% of the replacement cost.

CONCLUSION

No two high load impact events are the same. Damage to precast-prestressed girder bridge systems can be minor and easily repaired by maintenance personnel or severe requiring replacement of girders or entire spans under contract with experienced bridge builders.

WSDOT design criteria provide bridge engineers with a simple solution to improve the impact resistance of precast-prestressed girder bridge systems. Well distributed intermediate diaphragms and full depth diaphragms have been shown to reduce overall damage. WSDOT guidelines for repair design and assessment provide bridge engineers with a rational basis for determining if damaged girders should be repaired or replaced.

REFERENCES

1. Washington State Department of Transportation (WSDOT). 2012. *Bridge Design Manual*. M23-50. Olympia, WA
2. Qiao, P., Yang, M., McLean, D., 2008, Effect of Intermediate Diaphragms to Prestressed Concrete Bridge Girders in Over-Height Truck Impacts, Washington State Department of Transportation Research Report WA-RD 696.1, Olympia, WA
3. American Association of State Highway and Transportation Officials (AASHTO). 2012. AASHTO LRFD Bridge Design Specification. 6th Edition, Washington, DC: AASHTO.
4. Shanafelt, G., Horn, W. 1980, Damage Evaluation and Repair for Prestressed Concrete Bridge Members. National Cooperative highway Research Program report 226, Transportation Research Board, Washington, DC.
5. Shanafelt, G., Horn, W. 1985, Guidelines for Evaluation and Repair of Prestressed Concrete Bridge Members. National Cooperative highway Research Program report 280, Transportation Research Board, Washington, DC.