

# INVESTIGATOR'S SUMMARY<sup>1</sup>

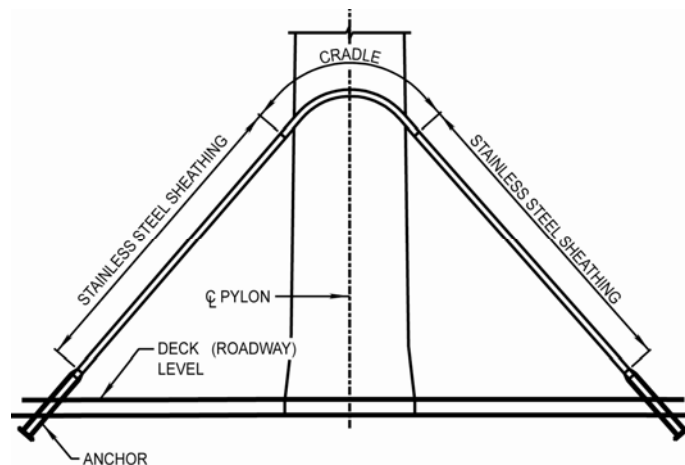
Nomination 2007-07

Investigator: Mustafa M. Saadi<sup>2</sup>

## CABLE-STAY CRADLE SYSTEM

### The Innovation

The cable-stay cradle system is installed in bridge pylons and uses individual sleeves to carry continuous strands of the bridge cable stays. This eliminates the need for anchoring at the pylon, and allows the strands to run parallel and act independently along their entire length as they travel from anchors at one end of the bridge deck, through the cradle in the pylon, to the anchors on the other side.

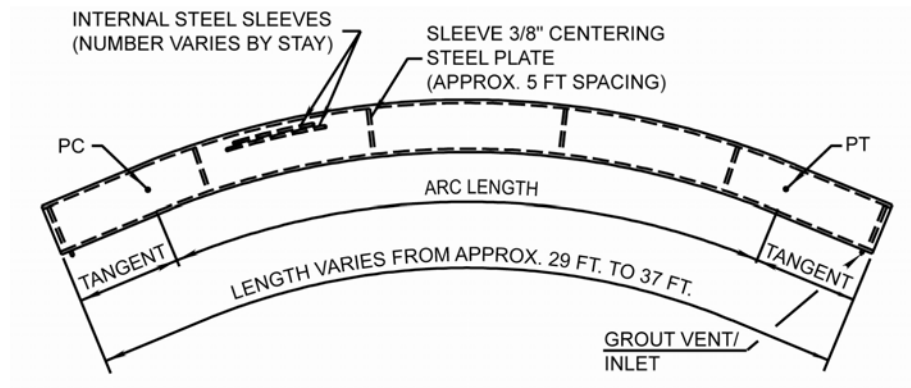


**Figure 1:** The stay strands run continuously from deck to deck through the cradle in the pylon

The bridge cable stays used are composed of a number of 7-wire strands depending on the design loads. Within the curved cradle, each individual strand is isolated through its own 1 inch diameter stainless steel sleeve. The sleeves are equally spaced throughout the cradle length using what is referred to as “cheese plates” at the cradle ends (due to the similarity to the holes in Swiss cheese), with axially placed sleeve-centering plates at intermediate spacing within the cradle.

<sup>1</sup> July 26, 2007

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**Figure 2:** Location of centering plates at the ends and along the cradle length.

The cradle is prefabricated off-site, the space between the internal sleeves is grouted under controlled conditions, and the cradle is then simply lifted into position at each stay level. The grout provides the natural transmission of compressive force from the strands to the pylon. The 7-wire strands are later individually inserted into position then stressed. The initially developed cradle weighs as much as 8,500lbs and is set into steel supporting frames that accommodates its geometry and facilitates its lifting and placement into final position, within a 1/4 inch tolerance. Setting one cradle into position, as claimed, took an average of half an hour.



**Figure 3:** The “cheese plates” at the cradle ends with grout in the interstitial spaces between the individual sleeves hold the strands parallel to each other.

The resulting continuous cable stays through the pylon eliminate the need for anchors at that location. Previous devices such as “banana” shaped saddle pipes also allowed the cables to be continuous through the pylon, however these caused the strands to be squeezed against each other, and they were usually grouted together permanently. In contrast, the cradle isolates the strands and keeps them unbounded which allows future inspection, removal, and replacement at any time without interrupting the traffic on the bridge.

The cradle is a simple solution that meets a number of structural needs. Its advantages and implications include the following major points:

- The absence of the anchors in the pylon eliminates the resulting large tensile forces, thus reducing the structural reinforcement and allowing a more slender pylon design, with all related savings in time and money.
- The cable allows the transfer of load to the pylon in a natural compressive form. Tests carried out using the cradle proved the possibility of using a larger number of strands per cable, which allows the use of fewer stays or longer bridge spans.
- Constructability of the bridge was improved by eliminating the need for anchoring platforms at high levels within the usually limited space in pylons.
- The fact that each strand is isolated allows quicker strand installation, and permits the use of mono-jacks to stress each strand individually at the bridge deck level instead of cumbersome jacks for stressing the entire stay.
- Maintenance of the bridge is significantly improved since strands act independently and are individually retrievable for inspection.



**Figure 4:** The cradle assembly is completed on site; it is fitted into a steel framework, and then lifted into position at each stay level.

## Application of the Innovation

Cable-stay bridges are becoming the design of choice for medium-length spans (between 500 and 2,800 feet). They require less cable, and can be built of identical concrete sections making them faster to build than suspension bridges. The cradle system has been developed for any cable-stayed bridge using 7-wire strands. Experts interviewed said that the cradle may be revised for use of other types of strands, as well as other bridge type such as suspension bridges. So far, the cable stay system was installed on two bridges:

### 1- *Veteran's Glass City Skywalk* – Toledo, Ohio (Ohio Department of Transportation)

The cradle was first developed for this bridge in close collaboration with the Ohio Department of Transportation (ODOT) and the Federal Highway Administration (FHWA). An accident with the truss placing approach spans halted the work for 18 months. However, the collapse which occurred on the bridge deck was un-related to the use of the cradle system in the pylon. The project was opened to traffic on June 24, 2007.

The introduction of the cable-stay cradle permitted the use of the largest number of strands in any cable stay bridge in the world (156 strands in a single stay, which is 70% more than the second-highest number to have been used in the US).

The use of the cradle allowed initial savings in the magnitude of \$4 million dollars for an initial contract price of \$220 million.



**Figure 5:** Glass being installed on the concave faces of the 23ft wide single pylon of the Veteran's City Skywalk Bridge in Ohio. The slender design was made possible due to the use of the cradle.

The four sides of the top 196 feet of the 261 feet high pylon was covered with backlit specially manufactured glass panels and other aesthetical elements that reflect the sky during the day and shine with more than 16million color combinations across the skyline at night, reflecting Toledo's industrial heritage of glass manufacturing. This aesthetic treatment along with the slender pylon design would not have been possible without the cradle system.



**Figure 6:** Inauguration of the Veteran's City Skywalk Bridge in Ohio with the LED backlit glass elements on all sides of the pylon.

2- *Penobscot Narrows Bridge and Observatory* – Bucksport, Maine (Maine Department of Transportation)

This bridge was the second design where the cradle was used. Due to the delays in the Ohio bridge project mentioned above (not related to the cradle) it was the first to stress stays in the cradle and to open for traffic on December 30, 2006.

The cradle was adapted to incorporate a pressurized inert gas system creating an air tight, continuously monitored space between the strands and the surrounding sheathing; in the cradle itself and in the stays from pylon to deck. The pressurized nitrogen gas engulfs the strands, cuts off oxygen, and thus controls corrosion.

The public's main concern for this bridge was to have the design revolve around the theme of granite for which the area is famous. The resulting pylons were designed as slender high granite obelisks. This was complemented by the construction of a multi level 360 degree panoramic view observatory at the west pylon. The observatory was made possible because the cable-stay cradle system saved space within the pylon and money within the project budget. The observatory is a first in the USA, the fourth bridge observatory in the world, the tallest occupied structure in Maine, and the highest public bridge observatory in the world.

Financial data for use of the cradle in the Penobscot bridge was not available due to the project delivery method. The design/build contractor stated that the overall project cost was “significantly less” using the cradle system as compared to pylon anchor based system. The project total cost is \$85 million dollars.

After the bridge completion, Maine DOT removed six strands from the stays of the bridge, and replaced them with carbon composite fiber material reference strands as part of a full scale long-term research for the future use of such material in bridge cables. This operation proved the cradle’s claim to ease of inspection and replacement of individual strands, and was done completely from within the bridge deck, with no interruption to traffic or visible work to the bridge users.



**Figure 7:** Two planes of stays and two pylons were used in the Penobscot Narrows Bridge and Observatory.



**Figure 8:** HDPE sheathing was used in combination with the cradles to achieve an air tight nitrogen filled seal around each stay.

|                            | <b>Veteran’s Glass City Skywalk<br/>Toledo, Ohio</b> | <b>Penobscot Narrows Bridge<br/>Bucksport, Maine</b>             |
|----------------------------|--|--|
| <b>No. of stay planes</b>  | single   | double   |
| <b>No. of pylons</b>       | 1  | 2  |
| <b>Stay sheathing</b>      | Stainless steel                                      | HDPE   |
| <b>Bridge Elements</b>     | Pre-cast   | Cast-in-Place  |
| <b>Aesthetical Feature</b> | Slender Backlit Glass clad Pylon                     | Granite similar Obelisk shaped pylons<br>+ panoramic observatory |

### **Background of the Innovation**

Development of the cable-stay cradle system was carried initially for the Veteran’s Glass City Skywalk project in Toledo, Ohio. In early 2000, the ODOT formed a team to assess and communicate the public’s perspective on the developing bridge design across the Maumee River. Requirements by the local community and organizations were:

- a “light” design reflecting the city’s glass industry heritage,
- a single pylon in the center of the river, and
- a single plane of cable stays between the two traffic directions.

The bridge pylon had to be slender enough to incorporate the glass theme elements, yet be able to carry the load from the stays.

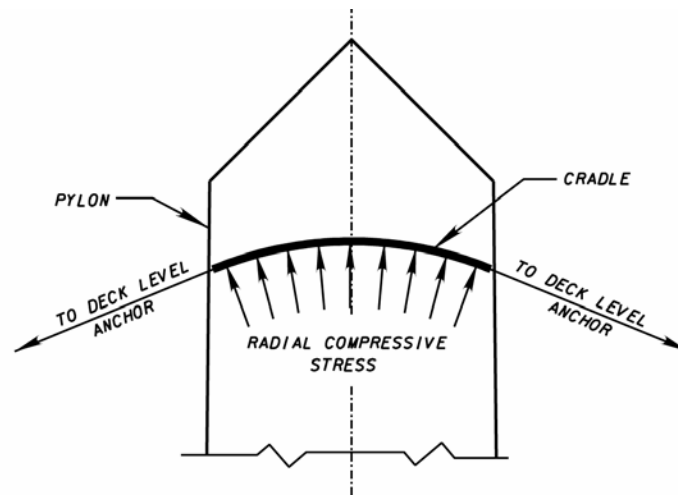
FIGG Engineers devised the cradle design which separates the strands as they pass through the pylon in their individual curved sleeves. The proposed solution thus reduced the tensile forces in the pylon and assured the smooth transition of loads relying on the natural compressive strength of concrete. Eliminating anchors at the pylon reduced its width by a third, from 31 to 23 feet, with resulting savings in quantity of reinforcing steel and concrete, and related construction costs. This also eliminated the critical stressing-linked operations at the otherwise limited space within the pylon structure as high as 230 feet above bridge deck.

The team leader for this design was W. Denney Pate, P.E. of FIGG Bridge Engineers. The patent for the cradle (U.S. Patent No. 6,880,193) lists the name of **FIGG Bridge Engineers, Inc.** Tallahassee, FL along with the following individuals from the company:

- Eugene C. Figg, Jr. (deceased)
- Linda Figg, President/CEO
- W. Denney Pate, Senior Vice President and Principal Bridge Engineer

The ODOT pre-purchased the whole cable-stay cradle system to facilitate the testing required by the FHWA, removing the testing from the Contractor’s responsibilities and the project’s critical path. The Cradle system manufacturer and supplier on both bridges where it has been used so far was Dywidag Systems International.

Initial Acceptance testing for the cradle design was done independently by the Construction Testing Laboratories (CTL) of Illinois. Testing was carried on full size samples according to the Post-Tensioning Institute (PTI) Recommendations for Stay Cable Design, and consisted of axial fatigue and ultimate static tests, axial fatigue and leak test, axial/flexural cradle test, and single strand axial testing.



**Figure 9:** Replacing the anchors at the pylon with the cradle eliminates the large tensile forces, allowing a reduction in the pylon mass and giving more flexibility for aesthetic pylon designs.

**Note on similarity to other existing systems:**

As mentioned in the first part of this report, the concept of cable continuity at the pylon (i.e. no anchors at pylon) is not a completely new idea. However, previous cable stay “saddle” systems used various mechanical means to create a fixed, non-sliding connection of the cable at the pylon. The use of these “saddles” created a bundling effect due to strand-to-strand friction, with the top strands squeezing the lower strands as cables got larger. This limited the number of strands that could be put together, and the largest number of strands achieved using this method had been 90 strands per stay. The cradle offers the possibility of an unlimited number of strands per stay as the cradle can theoretically be made as large as needed (depending on the physical limits of manufacturing and pylon construction dimensions). With the use of the cradle the largest number achieved so far was in the Ohio Bridge with 156 strands per stay.

The strand-to-strand friction was also considered by some experts to cause fretting corrosion in the strands. The fixing, often by grouting, of the bundled strands at the pylon prevented access to individual strands and meant that it was an all-or-none decision to replace the strands in a cable stay. The cradle eliminates the above mentioned problems by having the strands run parallel and independent from each other, thus eliminating the strand-to-strand contact, with possibility for individual strand inspection and replacement.

### **Responsibility for the Innovation**

Based on the available background information and collected material, the following are found to be responsible for the idea and design of the innovation and should be recognized should this innovation receive a NOVA award:

- **FIGG Bridge Engineers, Inc.** as a company, with **Mr. Eugene C. Figg, Jr. (deceased 2002)** and **Ms. Linda Figg**, current President/CEO.
- **Mr. W. Denney Pate**, FIGG Bridge Engineers, as concept innovator and system development team leader.

The innovators, Messrs. FIGG Bridge Engineers, stated that credit must also be given for testing and implementing the system to both the Federal Highway Administration, and the Ohio Department of Transportation, whose support allowed the timely, physical, full-scale testing of the system in order to verify its feasibility and performance. The responsible individuals from the FHWA and the ODOT, **Mr. Benjamin Tang** and **Mr. Mike Gramza** respectively, were interviewed as part of the following section of the report.

### **Opinions of Persons Contacted**

The investigator contacted FIGG Bridge Engineers, and a phone interview was conducted with Ms. Linda Figg (President/CEO) which was followed by the exchange of information through email. FIGG provided technical details, figures and illustrations, copy of the US Patent, and magazine article clips.

A phone interview was done with Mr. Benjamin Tang, P.E., Principal Bridge Engineer and Team Leader for the “long span, major bridges and tunnels group”, U.S. DOT, FHWA, Office of Bridge Technology. He is the expert and review authority for all bridge and structural matters for the Federal-aid bridge program, is responsible for drafting Federal polices and regulations, and championing the use of innovative bridge technologies.

Mr. Mike Gramza, P.E. provided his written answers on the questions raised by the investigator. Mr. Gramza was the project manager for ODOT on the Veteran’s Glass City Skywalk project for which the cradle system was initially developed.

Both Mr. Tang and Mr. Gramza provided positive comments about the system, and recommended that it merits an award. Both interviews are included in the attached selected interview summaries.

### **Investigator's Comments**

The cable-stay cradle system solved several challenges and issues in one simple design. It was thoroughly tested, approved by the FHWA, and proved to be a success in two landmark projects with demonstrated cost efficiency and ease of constructability.

While it was developed to satisfy certain aesthetical and engineering limitations of a particular project, the benefits and the advantages it confers have gone far beyond meeting those initial requirements. These include *design enhancement* (more slender, efficient, elegant designs, variety of pylon shapes), *construction improvements* (Reduction in construction costs, reduction in risky time consuming stressing operations, increase in stay size, longer bridge spans), and *life-cycle advancements* (simplified inspection, improved accessibility to strands, replacement of individual strands, research reference strands, service life predictable to be at least 100 years and can extend well beyond 150 years)

Furthermore, the cradle system has received several awards in the past two years namely:

- History Chanel's 2006 Modern Marvels Invent Now! challenge (top 25 inventions)
- ASCE Civil Engineering Forum for Innovation 2007 Charles Pankow Award
- National Society of Professional Engineers 2006 New Product Award
- Popular Science December 2006 issue on "Best of What's New"

The cradle and the two Bridge projects where it has been applied so far have been reported and positively commented upon in several articles (ENR, Popular Science, ASPIRE, Welding magazine, ACI concrete International, ASCE Civil Engineering magazine). The concept inventor and development team leader, Mr. Pate from FIGG Engineers, was recognized in the ENR January 1, 2007 issue among the top 25 individuals for "achievements, covered in the magazine during 2006, that served the best interests of the construction industry".

Note: All Illustrations and pictures are used courtesy of FIGG Engineering.

## SELECTED INTERVIEW SUMMARIES

### **Mr. Benjamin Tang, P.E.**

Federal Highway Administration  
Nassif Building, Room 3203, HIBT-10  
Washington, DC 20590  
Phone: 202.366.4592  
Email: [Benjamin.tang@fhwa.dot.gov](mailto:Benjamin.tang@fhwa.dot.gov)  
<http://www.fhwa.dot.gov/bridge/segmental/segtang.htm>

Phone interview by Mustafa M. Saadi on June 20, 2007.

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Mr. Tang was very helpful in presenting the advantages of the cable-stay cradle system, and comparing it to traditional cable-stayed technology based on his experience in the field and his job position in the Federal Highway Administration. Mr. Tang emphasized that the cradle has only been implemented so far for cable-stayed bridges. He described the difference between the cradle system and the conventional cable stayed systems used so far in the past 30 years:

- In conventional cable stayed bridges, there is a need for some sort of spacing/stacking between the strands in the pylon. The need for this vertical spacing was minimized by grouping the strands in the multiple sleeves provided in each cradle, which resulted in a reduction in the pylon height required.
- Also, in the conventional method, two separate discontinuous cable elements were needed, and the anchors were located at both pylon and deck level. With the cradle system, the introduction of the continuous stay cable allowed the use of anchors only at the deck level.
- The contact between individual strands in some previous systems usually causes fatigue stress and fretting corrosion. This was reduced in the cradle system by having strands in individual sheathing passing through the cradle.
- Constructability was not an issue, as the cradle and its supporting frame was lifted into position in both projects where it has been used so far.

Mr. Tang believes the “Cable-Stayed Cradle” system deserves distinction as it has solved and reduced a lot of problems and issues in the cable-stayed bridge system leading to the following major advantages:

- Reduction in pylon width and height, and thus cost of pylon construction,
- Reduction in stress fatigue in the strands,
- Safety during construction is improved by eliminating the anchoring activity at elevated levels at the pylons.
- The cradle element, to his knowledge, does not cost more, but less, than the eliminated anchors at the pylon,
- The system is easy to maintain, and individual strands can be replaced with relative ease.

**Mike Gramza, P.E.**

Project Manager, Ohio Department of Transportation

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Written reply on investigator's questions was received by email on June 26, 2007.

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**Q1 How does the innovation work with regard to its design, construction, use, and maintenance?**

A1 The Cradle has performed as intended by the design. It has greatly simplified construction of the bridge pylon and was relatively straightforward to install, align, and cast concrete around. The Contractor encountered no significant problems during installation of stay cable strands through the Cradle. Maintenance is expected to be minimal throughout its lifetime due to the use of high quality stainless steel alloys in its assembly.

**Q2 What is its effectiveness, and why does it merit an award? Is it in your opinion an innovation or merely an evolution of existing technology? Kindly describe what you think are the unique/innovative features of this system.**

A2 The Cradle is an efficient and elegantly simple way to minimize congestion of rebar and post-tensioning that would normally be needed in a pylon that had stay cable anchors embedded in it. It merits an award because it satisfies all concerns related to stay cables and how they attach to bridge pylons: it eliminates strand-to-strand interaction that would occur (and is considered by some to cause fretting corrosion in the strands) in a curved saddle pipe, it provides for stay strands to be parallel throughout their length – which enables virtually unlimited stay cable sizes and the ability to remove and/or replace individual strands as needed, and it eliminates the need for heavy, complex, and expensive steel anchorage boxes to reinforce the pylon in the stay anchorage region. While I believe the Cradle is an evolution in technology more than a raw innovation, it does provide significant freedom to the Designer to come up with virtually unlimited pylon cross-sectional shapes.

**Q3 Based on your experience, for what types of bridge projects is the cable stayed cradle system suitable? For what types of bridge projects is it not suitable?**

A3 The Cradle is suitable for use in the pylon of any cable stayed bridge in which the cables are comprised of 7-wire post-tensioning strands. This general suitability for any pylon shape or size is part of its appeal. The Cradle design would likely have to be revised if the stay cables were comprised of individual parallel wires).

**Q4 What are its similarities and differences to other “contemporary”/competing bridge suspension systems? How does it compare to these systems with respect to time, cost, safety, function, maintenance and life?**

A4 The Cradle is similar to the “banana”-shaped saddle pipes used on previous stay cable bridge designs in that it allows the stay cable to be one continuous tensile element that only anchors at deck level. It is also similar to systems that anchor at the deck and in the pylon in that it provides the ability to have strands running parallel to each other. It differs from the older saddle-pipe designs in that it eliminates strand-to-strand contact. It also differs from stays that anchor in the pylon because it transfers stay forces to the pylon concrete through natural compressive stresses, rather than high tensile forces which must be resisted with large amounts of rebar, post-tensioning, or large and complex steel anchorage boxes. The Cradle is much lighter and less complex than a steel anchorage box. It is much simpler to install in the pylon and place rebar and concrete around. Because picking weights are much lighter and the system is simpler to install, the Cradle makes pylon construction safer, quicker, and more efficient. From a maintenance standpoint, the Cradle itself is expected to be virtually maintenance-free. Its design allows us to remove and inspect individual stay cable strands during the service lifetime of the bridge as a part of a regular maintenance and inspection program. Because Cradles are much simpler to fabricate and install than large steel anchorage boxes, they are also expected to be less expensive.

**Q5 What have been the tangible benefits of the “Cradle” in the project where you have been familiar with its use?**

A5 The Cradle has provided many tangible benefits to the Veterans’ Glass City Skyway project. Because it keeps the strands parallel to each other, it allowed for the design of the bridge to incorporate the largest stay cables of any known bridge in the world. This allowed a lesser number of stays to be used than on similar projects. The significant reduction in concrete cross-sectional area in the pylon and the elimination of large amounts of rebar and post-tensioning (or the elimination of a steel anchorage box) resulted in reduced material use and costs to the project. Because the pylon cross-section could be minimized it allowed the pylon design to incorporate, for the first time on any bridge pylon in the world, glass panels and multicolor LED backlighting throughout the upper 190 feet of the pylon. Thus, the main pylon becomes a symbol of Toledo’s heritage in the glass manufacturing industry as it reflects the sky during the day and a brightly shining beacon lighting the way towards Toledo’s prosperous future at night.