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Investigation of the Chirajara Bridge Collapse

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International Association for Bridge and Structural Engineering (IABSE)

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Case Studies
3

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Preface

On January 15, 2018, at 11:49, the west pylon (B) of the cable-stayed Chirajara Bridge collapsed during construction of the bridge girder. The crossing is located approximately 20 km NW of Villavicencio, Colombia. The collapse led to the complete destruction of Pylon B, together with the erected span of the bridge girder. Authorities reported nine fatalities resulting from the collapse.

Shortly thereafter, the project insurer QBE Segures (Colombia) commissioned an independent investigation into the collapse of the bridge, through loss adjusters ONC Adjusters (Bogotá, Colombia). An international team of bridge engineering experts was assembled to undertake the investigation, with Professor Christos T. Georgakis of Brincker & Georgakis, Denmark as chair of the team. The other members of the team are Sven Eilif Svensson of ES-Consult and Klaus H. Ostenfeld of KHO-Consult in Denmark, Siegfried Hopf of Leonhardt, Andrä und Partner in Germany and Professor Yozo Fujino of Yokohama National University in Japan.

On May 30, 2018, the team issued a brief interim report on the causes of the collapse of Pylon B. Demolition of the standing east pylon (C) was recommended in the brief interim report, as it was nearly identical to Pylon B and subject to the same deficiencies as identified for Pylon B in this report. The expert team was informed that the demolition of Pylon C and the remaining parts of the superstructure was carried out on July 11, 2018.

On August 4, 2018, an extended interim report was issued, elaborating the findings presented in the brief interim report concerning the detailed failure mechanism of Pylon B. In addition, the extended interim report presented a general assessment of the overall bridge design and the corresponding design flaws throughout the bridge, as well as a brief geotechnical assessment.

All findings of the Brief Interim Report of May 30, 2018, and the Extended Interim Report of August 4, 2018, are presented and expanded upon in this book. The final findings of the team on the detailed investigation into the failure mechanism of Pylon B are reported in addition to a general assessment of the bridge design, the materials used for construction, and geotechnical aspects, whilst also presenting the observations made during site visits and interviews with all relevant parties.

The investigation has led to the following main conclusions:

- A detailed design check of the bridge, as defined in the engineering drawings and reports provided to the team, revealed several important design flaws.

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An Overview of the Forensic Investigation Process

John F. Duntemann, Senior Principal, Wiss, Janney, Elstner Associates, Chair, IABSE Task Group 5.1. Forensic Structural Engineering

Introduction

Engineering investigation of the causes of structural failures of buildings, bridges, and other constructed facilities, as well as rendering opinions as to the cause(s) of the failures, is a field of practice often referred to as *forensic structural engineering*.

The process of forensic structural engineering investigation is different from conventional structural engineering design. An engineer performing a forensic structural engineering investigation generally has the benefit of the evidence, which, if well-documented and correctly analyzed, can explain how and why the failure or collapse occurred.

The investigation of structural failures generally consists of the following tasks:

- First response and preliminary assessment
- Development of investigation plans and protocols
- Fact gathering and document review
- Engineering analyses to determine the cause(s) and responsibilities
- Reporting on the findings of the investigation
- Recommendations on how to avoid repeating the same mistakes

The investigation of the Chirajara Bridge Collapse as reported in this book includes many of the elements described above.

Fact Gathering

The collapse of the cable-stayed Chirajara Bridge near Villavicencio, Columbia occurred during construction on January 15, 2018. There were reportedly nine fatalities due to the collapse.

The experts in charge of the independent investigation were retained by the project insurer to determine the cause of the collapse. They were allowed access to the site on two separate occasions, March 20, 2018, and March 22, 2018. The first site visit included access to the collapsed Pylon B and Abutments A, and the remaining (uncollapsed) Pylon C and Abutment D.

Before the Collapse

The status of construction immediately prior to the collapse was determined from various videos of the bridge that were recorded on the day of the collapse. No unusual construction work was being performed at the time of the collapse. A review of the available wind and temperature data prior to collapse also did not indicate any unusual conditions or extreme changes. While three minor seismic events were recorded on the day of the collapse within a radius of 200 km from the bridge site, it was concluded that these seismic events did not contribute to the collapse.

During and After the Collapse

Video footage of the collapse and 55 minutes prior to the collapse was available for review by the investigators. The video footage indicated no significant wind conditions or ground movements at the time of the collapse. The duration of the collapse was about 7 seconds which started with slacking of the shortest main span cables and ultimately the collapse of Pylon B.

Subsequent examination of the debris pile indicated that the structural components of the pylon ended up almost directly below their original (pre-collapse) position on the longitudinal axis of the bridge. The investigators observed that both the southern and northern lower pylon legs had separated from the diaphragm along the entire length of the legs by rupturing all the horizontal reinforcement at the inner face of the lower pylon leg. The pylon head was observed to be largely intact, except for damage by concrete crushing and ruptured reinforcement where the head was connected to the upper pylon legs.

Interviews

The general contractor, the design engineer, the site engineer, and the cable supplier were all interviewed as part of this investigation. These interviews provided important information and clarifications regarding the design of the bridge and the construction sequence and methods.

Engineering Analyses

Design Review

A review of the bridge design indicated several significant design deficiencies including a severe lack of bracing tie capacity of the link slab and diaphragm for design loads, service loads, and during erection; the bearings did not have sufficient capacity to withstand the calculated shear forces and deformations during construction and for the service stage design loads; the anchor beam assembly was inadequately designed for service loads; the pylon head was inadequately designed for the calculated longitudinal forces; the transition beam and corresponding connections were not designed with sufficient tension capacity; the longitudinal edge beams of the girder were inadequately designed; and the girder concrete slab was not sufficiently reinforced in large negative moment areas.

Geotechnical Review

A review of the original geotechnical investigation and the foundation design was also performed as part of the forensic investigation. The investigators concluded that the failure of the pylon was not caused by unforeseen settlements, lateral movement, or induced loads through failure of the tieback anchors, earthquakes, or other geotechnical factors.

Material Sampling and Tests

Material samples were taken from the collapsed bridge to determine their condition and material properties. These samples included concrete cores, steel reinforcement, steel tendons, and steel plates.

Finite Element Analysis

A detailed material and geometrical non-linear finite element analysis (FEA) of the collapsed bridge was performed to determine the collapse mechanism and the cause of the collapse. The purpose of the FEA was to analyze the actual structure and the actual loading at the time of the collapse. Thus, no load factors or capacity reduction factors were applied to the loads or the materials. The material properties were based upon the material testing mentioned above.

The FEA determined that the lateral connecting reinforcement between the pylon and diaphragm ruptured in the upper corner of the diaphragm after the external load caused deformations that exceeded the local ultimate deformation capacity. It was determined that the external load reached the level necessary for collapse three days after the last major construction activity, i.e., pouring of the concrete deck, and was attributed to several normally inconsequential factors or their combination. After the rupture of the upper lateral reinforcement, the connection between the diaphragm and the lower pylon legs failed in a non-ductile asymmetric manner, so that the south pylon leg detached from the diaphragm by an “unzipping” of the lateral reinforcement through the sequential rupturing of the whole diaphragm.

Reporting and Recommendations

A detailed review of the bridge design, as defined in the engineering drawings and reports provided to the investigators, revealed several important design flaws. The primary design deficiency was determined to be the inadequate lateral tie capacity between the knees of one of the two pylons. It was further determined that the sudden nature of the collapse was due to the non-ductile design of the diaphragm between the lower legs of the pylon. The investigators recommend that projects of this scale and importance are properly peer-reviewed and the procurement methods are improved.

Summary

The collapse investigation described in this book is a good example of a proper forensic engineering study. The information before, during, and after the collapse of the Chirajara Bridge is well documented and provides the basis for an accurate engineering analysis of the cause of the collapse. The subsequent bridge design review, the non-linear finite element modeling, and material sampling and testing served to correlate the information, or evidence, with the collapse mechanism and cause of the failure. The illustrations in Chapter 9 of the book are particularly illustrative when compared with the condition of the remaining east pylon that did not collapse. Finally, the recommendations, or lessons learned, in the book provide useful insights on how this collapse could have been avoided and will hopefully be referenced when constructing similar structures in the future.

Chapter 1

Description of the Structure

The Chirajara Bridge was situated in the Guayabetal municipality of Cundinamarca Department, nearly 20 km WNW of Villavicencio, capital of Meta Department, and approximately 60 km SE of Bogotá. Located at kilometer mark 64 of the National Route 40, the Chirajara Bridge formed part of a large infrastructure project of Agencia Nacional de la Infraestructura (Public Authority of the Colombian Government). The plan included a dual carriageway between Bogotá and the Eastern Plains of Colombia.

Excavation for the foundations of the bridge was initiated by the former constructor TRADECO in 2014. Later, in 2016, TRADECO's contract was terminated, whereupon the constructor, GISAICO, was appointed by the main contractor, CONINVIAL, to finalize

Fig. 1.1 Pylon C, identical to Pylon B, of the cable-stayed Chirajara Bridge

Chapter 2

Assessment of the Bridge Design

The overall assessment of the bridge design has been performed based on information provided in the design drawings and the engineering design report. The team of international experts commissioned Leonhardt, Andrä und Partner, Germany, to undertake a detailed engineering design check of the bridge, with checks based on *strength load combinations* as required by AASHTO [10]. Additional checks were also made according to Eurocode [8, 9].

2.1 Bearings

An unconventional solution for the bridge bearing design was chosen, containing two elastomeric bearings for vertical support of the girder at each pylon and two inclined elastomeric bearings for each of the stay anchor cables on the anchor beam at the abutment.

Equilibrium of the structure in both longitudinal and lateral direction was achieved through elastic support via deformation of the elastomeric bearings, as no rigid supports, or anti-lifting devices were provided between the girder and the substructure. This resulted in a somewhat *"floating"* statical system leading to excessive displacements for both the service and collapse stages. Generally, the displacements found at the bearings exceed those allowable in both the longitudinal and lateral directions. For service stage loads, it could be expected that some of the bearings would have sheared off.

Expansion, contraction or longitudinal movement of the girder, e.g., due to temperature deviations and breaking forces, would have led to deformation of the elastomeric bearings in shear as well (see *Fig 2.1a* and *2.1b*). Because of the inclination of the bearings, this would have resulted in an upward or a downward displacement of the girder. Hence, these displacements would have led to the girder no longer being level with the rigid abutment. In addition, it was found that lateral (transverse to the bridge axis) displacements of the anchor beam would have been caused by the lateral component of the anchor cable force (see *Fig 2.1c*).

Chapter 3

Status of Construction and Loads Immediately Prior to Collapse

3.1 Construction Sequence and Status Immediately Prior to Collapse

The general construction sequence of the main structural components is presented in *Fig 3.1*. The construction status at the end of specifically chosen months is presented in *Fig 3.2* to show how the structure was progressing during construction.

As the side spans (AB and CD) were erected before cable installation, the girder was not erected by the typical balanced cantilever method. Although this method was initially proposed, the side spans were eventually erected on temporary supports to save time (see *Fig 3.2c and 3.3a*).

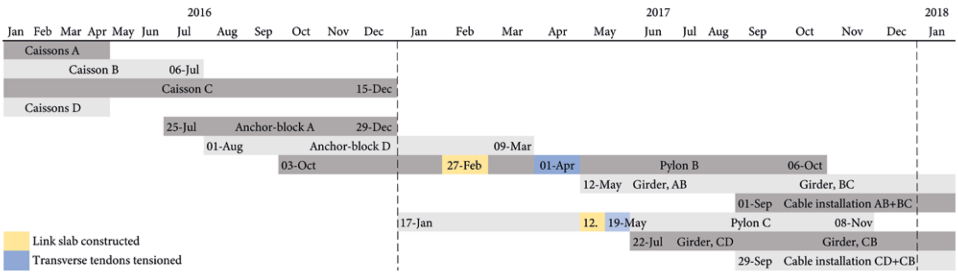

Fig. 3.1 Overview of the general construction sequence

As seen in *Fig 3.3b*, the main-span sections were erected by use of trolley cars. These were supported by cables, anchored in the anchor blocks, and supported at the diamond top of the pylon legs. To balance the cantilever main-span sections, the stay cables were tensioned immediately after pouring of concrete on each of the girder sections. The temporary supports at the side-span sections were released immediately before tensioning of the respective side-span stay cables (see *Fig 3.2c*).

Chapter 4

Description of the Collapse

The nature of the collapse of Pylon B can be established in two ways. One is by assessing the footage from a nearby traffic camera, which had the majority of Pylon B and the western main- and back-span in its field of view and filmed during the entire collapse. The second is by evaluating the orientation and placement of the various structural elements from the debris zone after the collapse.

4.1 Video of Collapse

The team was provided with video footage of the collapse and 55 minutes leading up to the collapse [D10]. The video camera was situated next to a nearby road north of the bridge filming towards south (see *Fig 4.1* and *4.2*). The video was filmed at ~15 frames per second with a resolution of 1280 × 720 pixels. The part of the view containing the bridge has a resolution of 285 × 285 pixels. The video was split into separate frames and then stabilized and corrected by image translation and rotation with the software Hugin to reduce wind-induced camera motions.

Fig. 4.1 Still frame from traffic camera video immediately before collapse

Chapter 5

Site Visits

Collaborators of ONC were on site on several occasions, including the days following the collapse, on January 16–17 and on March 1. Photographic records and drone videos from these visits were provided to the team.

Members of the team were allowed access to the site on two separate occasions, namely March 20 and March 22. The first visit included access to both the standing Pylon C and Abutment D as well as the collapsed Pylon B and Abutment A. The second visit included access to some of the more difficultly accessible elements in the debris zone.

5.1 Pylon B and Abutment A

5.1.1 Pylon Foundation Caisson

The foundation caisson cap and the part of the circular mono-caisson extending above ground showed no sign of damage, settlements, or movements. Only superficial damage to the caisson cap was detected (see *Fig 5.1* to *5.3*). Severe damage was found on top of the caisson cap in the construction joint with the lower pylon legs and the diaphragm (see *Fig 5.4*). Damage in the construction joint included crushing of concrete and rupturing of connecting reinforcement.

A brief internal inspection of the circular caisson revealed no sign of damage or variations on the inside caisson wall.

5.1.2 Lower Pylon Legs and Diaphragm

It was observed on site that both the southern and northern lower pylon legs had separated from the diaphragm along the entire length of the legs rupturing all connecting horizontal reinforcement immediately at the inner face of the lower pylon leg (see *Fig 5.5* to *5.9*). No reinforcement pull-out failure was observed. Apart from the separation from the diaphragm, both lower pylon legs showed severe damage by concrete crushing and reinforcement rupture at the base and knee level, resulting from hinge formation at these joints (see *Fig 5.10*, *5.12*, and *5.13*). Additionally, the southern lower pylon leg showed severe damage by concrete crushing and reinforcement rupture, localized around mid-

Chapter 6

Interviews

Participants involved in the design and construction of the Chirajara Bridge were interviewed to clarify several issues. The general design philosophy behind the bridge as well as the construction sequence and methods were of particular interest. The interviews took place in Colombia between March 21 and 23, 2018. Excerpts from these are presented in this section.

6.1 Interview with the Main Contractor

March 21, 2018, Fabio Forero from the main contractor, CONINVIAL, was interviewed to clarify the construction sequence and to provide information regarding various issues, which turned up during construction. Excerpts from Mr. Forero's statements follow.

A drill was initially used for removal of soil from the excavation for the caissons, but when rocks became harder, dynamite was used.

The initial design depth of Caisson B was 30 m. During excavation, the former constructor, TRADECO, wanted to go deeper to find better soil conditions. The caisson was eventually founded at a depth of 34.4 m. However, here the soil was found to be in the same condition. Mr. Forero stated that the former designer, E.D.L. Ltda., specified that the foundation should not be modified any further, as it had already been evaluated by many specialists.

The link slab was not poured monolithically with the pylon legs. Only the twelve tendons in the link slab went through the pylon legs. Mr. Forero showed a construction photo of this, depicted in *Fig 6.1.*

During casting of the upper pylon legs, temporary horizontal steel tubes were installed between these to avoid big internal moments in the pylon legs until they were connected at the top. Mr. Forero showed a construction photo of this, depicted in *Fig 6.2.*

A balanced cantilever construction process of the girder was originally the idea of the former constructor, TRADECO. However, when GISAICO took over the construction work, this method was changed to a temporary supported girder, going from the anchor block to the pylon. This change was made by GISAICO to save time. The design engineer agreed with this change and redid all the calculations to approve this. *This statement contradicts a statement later made by the designer (see Section 6.2), and no engineering design calculations regarding the construction phase have been provided to the team.*

Chapter 7

Geotechnical Investigation and Foundations

The team of experts commissioned Smoltczyk & Partner, Germany, to undertake an assessment of the geotechnical investigation and foundation design. This assessment has been based on information provided in design drawings, geotechnical design reports, and calculations conducted by TERRATEST S.A.S, Colombia.

7.1 Assessment of Geotechnical Investigation and Design Reports

The geotechnical investigation and design reports follow generally accepted rules of technology, in that they cover the usual scope of work for site investigations and geotechnical designs. Particularly for the abutment and Caisson B on the Bogotá side, the investigation covers:

- Consideration of topography and geomorphology
- Regional geological setting and tectonics
- Structural geology based on field mapping and boreholes
- Description of the colluvium and underlying weathered phyllite rocks in terms of their structure, discontinuities, strength, and deformational characteristics
- Hydrogeological analysis and drainage
- Subsurface geological / stratigraphic model based on boreholes and geophysical surveys
- Definition of characteristic geotechnical parameters based on rock mass classifications, laboratory tests and back calculation of existing colluvium slopes
- Numerical analysis of seepage in the slope and drainage via the caisson
- Investigation of alternative foundation types under consideration of the loads known to the geotechnical engineer at that time (e.g., $Z \approx 122\,\text{MN}$ vertical load)
- Geotechnical design calculations for the chosen Caisson B (Pile 1 in the initial reports), with depth 34.5 m and diameter 8 m, including:
  - Stability of permanent slopes and construction pits
  - Stability and serviceability of foundation elements, regarding the earth pressure on the caisson shaft

Chapter 8

Material Sampling and Tests

Field samples were taken from the collapsed Chirajara Bridge for the purpose of determining their condition and material properties. The field samples included concrete cores, steel rebar, steel tendons, and steel plates for test at the Technical University of Denmark (DTU) in Copenhagen, Denmark. In addition, samples of concrete cores and steel rebar were sent for test at Los Andes University in Bogotá, Colombia.

8.1 Sample Extraction

Field samples were taken from the collapsed portion of the bridge during the period of March 22 to April 11, 2018. The subcontractor in charge of the field sample extraction was PROCIESTRUCTURAS S.A.S., that provided the personnel and equipment required for the work. The specific details of the structural members and locations from where the samples were to be taken were coordinated with Brincker & Georgakis ApS. As a result, 25 zones were identified in the collapsed portion of the bridge where concrete cores, steel rebar, steel tendons, and steel plates were extracted from these zones. The samples were identified with six prefixes:

- Prefix 1: Letter Q for the insurer QBE
- Prefix 2: C for testing in Colombia and E for testing in Europe
- Prefix 3: Number to identify the zone from which the sample was extracted
- Prefix 4: Letter to identify the type of sample; N – Concrete core, S – steel reinforcing bar, T – steel tendon, L – steel plate
- Prefix 5: Number of samples from zone
- Prefix 6: Letter for condition of sample

The field samples were extracted from representative parts of the bridge including the column leg (pylon leg), diaphragm, slab on diaphragm (link slab), dado de transición (caisson cap), and the main girder.

After extraction, the samples were packaged and sent to the testing laboratories in Colombia and Denmark. Due to the collapsed condition of the bridge, many of the samples, extracted from the rubble, were likely damaged or otherwise impaired for testing under prescribed conditions. All testing was aimed at achieving the code-defined conditions for

Chapter 9

Detailed Investigation of the Collapse of Pylon B - West

A detailed material and geometrical non-linear finite element (FE) analysis of the collapsed structure was conducted to establish an accurate collapse mechanism and to determine the main cause of collapse. A thorough description of the FE-model, as well as the outcome of the analysis, is presented herewith.

The purpose of the FE-model is to reflect the actual structure and the acting load at the time of collapse. Thus, no safety or modification factors have been applied to either the material properties or the loads. The material properties aim to reflect the actual behavior which could be expected, based on the material tests and the bridge design.

Prior to the detailed FE-model, presented in this section, a simple independent preliminary model was established by analytically derived equations and solved by numerical integration. The simple model indicates similar behavior of the structure and identical mechanisms with respect to the collapse as found by the detailed FE-model presented in this section.

The finite element software SOLVIA was used for the detailed investigation of the Pylon B collapse.

9.1 FE-Model Description

The structure was divided into different structural components. Each component as well as the connections between them were modeled to reflect the actual behavior of the overall structure.

9.1.1 Statical System

The general static system of the FE-model is seen in *Fig 9.2*, whereas the detailed modeling of boundary conditions can be seen in *Fig 9.3*.

To establish a reliable analysis, resembling the actual structure prior to collapse, the temporary bracing stays from the caisson cap to the girder were not included in the analysis. These were excluded since it was unclear how many of the strands were provided, how many were tensioned, and to which level they were tensioned (see *Fig 2.21*, Section 2.9).

Chapter 10

Pylon C - East

Apart from the depth of the foundation caissons, Pylon B and Pylon C were identical in their structural design and configuration. Furthermore, the superstructure supported by Pylon C was slightly behind Pylon B in construction, leading to an approximately 82 ton load deficit for Pylon C in relation to Pylon B (see Section 3.2.1). An inspection of standing Pylon C revealed the existence of two discrete vertical cracks in the diaphragm, starting from the uppermost corners, as can be seen in the photos in *Fig 10.1*. From this, it is seen that Pylon C reacted in the expected manner to the progressively increasing construction loads, i.e., through concentrated cracking of the diaphragm in the uppermost corners and, as a consequence, concentrated strains in the connecting reinforcement between the diaphragm and the pylon legs. This is described in this report as the first stage of collapse of Pylon B. Therefore, it is reasonable to conclude that Pylon C was on the verge of collapse before it was demolished. As its load deficit in relation to Pylon B was the main reason for it not collapsing before its demolition, any additional loading due to, e.g., working activities, vehicles, equipment, extreme temperatures, wind, or seismic actions, could have led to a collapse of the pylon, in a similarly catastrophic manner to what was observed on Pylon B and again without warning.

This does not imply that Pylon C could not have been hypothetically salvaged. Having identified the bridge deficiencies, appropriate strengthening and retrofit of the pylon, cables, girder, anchorages, and abutments could have yielded a serviceable part of a new bridge. What should be made clear though is that the risk to human life and the poten-

Fig. 10.1 Pylon C discrete vertical cracks in the uppermost corners of the diaphragm

Chapter 11

Project Organization

The international panel of experts commissioned Leonhardt, Andrä und Partner, Germany, to undertake a review of the available documents, detailing the project organization behind the Chirajara Bridge. Key findings and observations are presented herein.

11.1 Reviewed Documents

Several documents have been reviewed, most of which were written in Spanish. However, the outcome of this review has been conducted in English, aiming to keep the meaning and philosophy of the original Spanish wording. Key findings and observations were based on the following supplied documents:

- Design and Build Contract (D&B) no. 123-OT-032-005 between CONINVIAL and GISAICO
- Specifications for Construction
- Regulations of Construction Works
- Control and Inspection Plan during Construction
- Phase II Design
- Minimum Personnel
- Quality Management System
- Plan for Technical Control
- Minutes of Follow-Up meetings during construction

11.2 Organization and Contractual Background

The Chirajara Bridge project was a part of a large national infrastructure plan, involving several parties. The parties involved, and their relationships, have been examined. In addition, an organizational chart summarizing these relationships is shown in *Fig 11.1*.

Agencia Nacional de la Infraestructura (ANI): Public Authority of the Colombian Government, Owner of the infrastructure. ANI subcontracted COVIANDES to operate several sectors, part of a large infrastructure plan, including a highway between Bogotá and Villavicencio.

Chapter 12

Recommendations

12.1 General

The causes for the total collapse of the Chirajara Bridge, Pylon B, and its associated superstructure under construction have been extensively covered in the preceding sections of this report.

The review of the design used as the basis for the construction, the post-collapse observations on site, and subsequent re-analysis of the bridge structure as designed, as well as a Category III independent check have revealed that the design was inadequate for its purpose. For details refer to the *Executive Summary* and the other sections of the report.

Although the immediate cause for the collapse was identified to be insufficient strength of the horizontal tie between the "knees" of the pylon, the project was also found deficient in many other structural and organizational respects. It has been determined that the collapse of the bridge would have been always imminent after erection of the pylons and application of loads during construction or in service.

After this catastrophic event, it is important to try to understand how and why this catastrophe happened. How could such a fatal design error be committed, and why would it pass unnoticed in subsequent phases of the work? As it is most often the case, based on experience from previous investigations of for example crashes of transport vehicles and airplanes, it is rarely one single cause that leads to catastrophic failures, but rather a succession of events which individually could often be dealt with, or prevented from having any consequences, but collectively accumulate beyond ability to handle and eventually cause the inevitable crash.

For the current investigation it is, therefore, necessary to review and analyze the process for the construction of the bridge facility from the initial contracting of the concession by the Owner to the Operator and via the Construction contract to the Main Contractor to the Design and Build Contract for the Bridges, including subcontracts to the designer and suppliers. These comprise key elements of the overall description of the project intentions, including required criteria of safety, as well as operation and maintenance requirements throughout the life of the facility. The procurement of construction firms, procurement of design firms, handing over to the Operator with maintenance instructions and manuals, etc. as well as setting up a suitable operation, inspection and maintenance program for the bridge are key components to outline. Such a review has

Chapter 13

Lessons Learned

Laurent Rus Jenni, Founder and CEO at Singular Structures Engineering

13.1 Preamble

Whenever a structural collapse occurs, engineers should take a moment to reflect on working methodologies from governance to operation and maintenance stage corresponding to the life cycle of the structure, including planning, design, commissioning, and construction stages. Moreover, if the information is shared by the involved parties with maximum transparency and collected within the shortest time possible, it is the whole of the structural engineering practice that benefits from a continuous learning process, contributing to the “state of the art” of civil engineering.

This report on the Chirajara bridge collapse has clearly shown several aspects of our bridge engineering practice that tend to be overlooked, either by pressure of time or budget, both aspects that jeopardize the safety of civil engineering projects entrusted to engineers by society.

This report highlights in great depth a) how the bridge design was flawed on several key structural elements, b) the lack of standard use of technical documents and procedures, and c) a non-robust contractual organization, as three basic elements which have led to the failure of the structure.

During the investigation process, the triggering effect of the Chirajara Bridge collapse was identified to have occurred during the construction stage where construction loads already exceeded the design load at the pylon knee with the corresponding detailing between tower leg, diaphragm, and link, which has low ductility, leading to a sudden collapse of the structure.

While the triggering effect and first location of structural failure have been described, the report also shows multiple potential locations for partial or total collapse and how these design flaws were neglected by engineers over the different stages of the project.

The availability and the openness during the interviews of the main contractor, design engineer, site engineer, and cable supplier and their acceptance to be interviewed by the independent investigation team, which was composed of structural engineering experts lead by Professor Christos T. Georgakis, have to be stressed. This openness should not be taken for granted but should be appreciated for the benefit of a constantly evolving practice of bridge design and construction.

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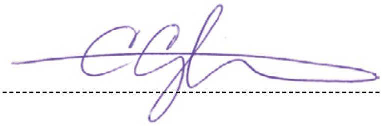
Notation

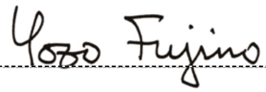
Throughout the report, all unspecified units are defined according to the SI system.

ε	=	strain
ε_c	=	strain at maximum concrete compressive stress
ε_{ct}	=	maximum concrete tensile strain
ε_{cu}	=	ultimate concrete compressive strain
ε_s	=	steel strain
ε_y	=	yield strain
ε_u	=	ultimate strain
ε_{bu}	=	bond ultimate strain
ε_{su}	=	ultimate steel strain
$\varepsilon_{RC,u,sing.}$	=	ultimate strain of reinforced concrete member with single crack formation
$\varepsilon_{RC,u,dist.}$	=	ultimate strain of reinforced concrete member with distributed crack formation
f_c	=	concrete cylindrical compressive strength
f_{cu}	=	concrete stress at maximum compressive strain
f_{ct}	=	concrete tensile strength
f_y	=	steel yield stress
f_{su}	=	ultimate steel stress
$f_{y,eff}$	=	yield stress, effective cross section
$f_{u,eff}$	=	ultimate stress, effective cross section
f_{GUTS}	=	guaranteed ultimate tensile stress
σ	=	stress
σ_s	=	steel stress
σ_c	=	concrete stress
σ_N	=	axial stress
τ	=	bond stress
$\tau_{b,max}$	=	maximum bond stress
δ	=	relative bar-concrete slip
A_2^*	=	torsional flutter derivative
A_s	=	reinforcement area
A_c	=	concrete area
A_p	=	strand area
$\o_s$	=	reinforcement bar diameter
F	=	force
R	=	support reaction
N	=	axial force
V	=	shear force
V_s	=	shear capacity
M	=	moment
L	=	length
E	=	modulus of elasticity
E_s	=	modulus of elasticity, Steel reinforcement
E_p	=	modulus of elasticity, steel strands
E_0	=	initial modulus of elasticity, concrete
E_h	=	hardening modulus, Steel reinforcement
ν	=	Poisson's ratio
γ	=	specific weight
λ	=	local punching coefficient
θ	=	concrete shear crack inclination
s	=	spacing
s_{rm}	=	mean crack distance
l_p	=	plasticized length of bonded bar
k	=	spring stiffness
$\rho_{s,l}$	=	longitudinal reinforcement ratio
$\rho_{s,H}$	=	horizontal reinforcement ratio
$\rho_{s,V}$	=	vertical reinforcement ratio

The Investigators



Christos T. Georgakis
Aarhus, Aug 31, 2018



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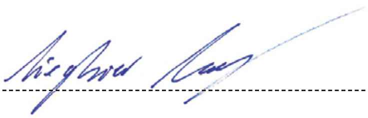

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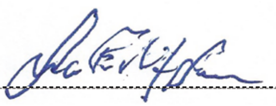

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Copenhagen, Aug 31, 2018

Case Studies

Objective:

To provide in-depth information to practicing structural engineers, in reports of high scientific and technical standards through case studies on design, rehabilitation, forensic engineering and other topics.

Topics:

Structural analysis and design, dynamic analysis, construction materials and methods, project management, structural monitoring, safety assessment, maintenance and repair, and computer applications.

Publisher:

The International Association for Bridge and Structural Engineering (IABSE) is a scientific / technical Association comprising members in 90 countries and counting 58 National Groups worldwide. Founded in 1929 it has its seat in Zurich, Switzerland. IABSE's mission is to promote the exchange of knowledge and to advance the practice of structural engineering worldwide. IABSE organizes conferences and publishes the quarterly journal Structural Engineering International, as well as conference reports and other monographs, including the SED series and Case Studies. IABSE also presents annual awards for achievements in structural engineering.

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Investigation of the Chirajara Bridge Collapse

On January 15, 2018 at 11:49, the west pylon of the cable-stayed Chirajara Bridge collapsed during construction of the bridge girder. The collapse led to the total destruction of the pylon, together with the erected span of the bridge girder. Authorities reported nine fatalities resulting from the collapse.

In this case study, the findings of the detailed investigation into the failure mechanism of the bridge are reported. In addition, selected drawings used for construction, geotechnical aspects, and deficiencies in the bridge design are presented, together with observations made during site visits and interviews with relevant parties.

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