

The history of bridge collapses

Limitations on technical constructions

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History is often about success stories. This paper is the opposite – it will analyse collapsed bridges, where an important link in the transport network suddenly disappears. There are a wide range of reasons for the collapses: some have manufacturing defects and design flaws or poor construction combined with poor maintenance, while others collapse from floods, fires, earthquakes, or impacts from boats, railways, or other means of transportation.

This paper also describes the technical development of bridges and shows the actual limitations of specific construction methods and materials. Building larger bridges often means longer spans – this is a challenge that stretches the engineering work to its limits. The business has an ever ongoing effort to develop better construction in an area that is not an exact science.

On a fine Sunday, May 4, 1873, the Baptist Church in Dixon, Illinois planned to baptize six converts in the Rock River. A large share of the town's more than four thousand inhabitants followed the baptism, and several hundred went on the west side of a new bridge to follow the service on the north bank of the river. The bridge was built by thin cast iron pieces put together in a truss bridge with pedestrian lanes on both sides of the road lane.¹

Suddenly, a loud sound was heard from the first of the bridge's piers. The north span fell into the water, followed quickly by the south span, while the remaining three spans were demolished but remained standing. Most people on the bridge fell into the cold water six meters down and everything became chaotic when they tried to swim to safety.

The consequences of the collapse were catastrophic. During the next days the churches in the little town buried 46 victims.

Who was to blame?

Was it the crowd on only one side of the bridge that made an overload? Was it the local politicians who had voted for this poor bridge design? Was it the constructor who had delivered a faulty design? Were the cast iron rods used to make the bridge of bad quality? Or did the bridge inspection by the local authorities miss loosened bolts?

As with many similar accidents, there was not one single cause found, and the causes found are always debatable. It is often several incidents that lead to an expensive and fatal result.

The study of accidents

This is one of several thousand severe bridge collapses throughout history. Construction engineers have to rely on experiences and their creativity when striving to build larger bridges. This is especially true in the world of bridge engineers, where larger spans are central. With larger spans the sides of a large valley or river can be connected or islands can be connected with the mainland. The better infrastructure creates faster and cheaper transport, resulting in higher prosperity.

But structural engineering is not an exact science. New designs, standards, and procedures give new possibilities and new issues as well. A large part of the technical knowledge associated with bridge engineering is based on past failures. Only when a structure fails are the boundaries of a method discovered and can be studied and understood. From this, new theoretical models and formulas can be developed.

A new direction within the engineering field has arisen – forensic engineering. As a researcher has said, “What sort of doctor should study only healthy persons?”² This new area in science fo-



Fig. 1. The dedication of Dixon's Bridge, 1869. At left the old bridge made by wood. At the entrance a toll booth at left.

Fig. 2. The Dixon Bridge just after its collapse, 1873.



cuses on the investigation of failures caused by materials, products, structures, or components. In principle it is an old field, but now all large bridge accidents are investigated and reported internationally. The *Journal of the National Academy of Forensic Engineers* has been published since 1984, established by the academy formed in 1982. In addition, the *Journal of Performance of Construct-*

ed Facilities started in 1987 and *Engineering Failure Analysis* began in 1994. Case studies are now a central part of civil engineering education.³

When the Fiskebæk bridge in Denmark collapsed in 1972 a bridge expert commented that he "was disappointed" with the accident because it was caused by faulty piling and this was "un-

interesting from a construction point of view". The fault could not lead to new recognition in the area of structural engineering. His opinion was that other accidents had almost "paid off".⁴

Research on bridge collapses is mostly based on case studies. Two books in this field are recommended. In *Understanding Bridge Collapses*, Björn Åkesson analysed 20 bridge accidents through their history, construction, and the details around their accidents. The interested specialist can read formulas and other technical details. The other book is Joachim Scheer's *Failed Bridges. Case studies, Causes and Consequences*, in which he analyses 536 failed bridges with a short resume over the incident and the cause of each failure.

A comprehensive world-wide database of the most important bridge collapses in history does not exist, and reliable statistics over the causes for the accidents, their geographical location or time of occurrence, are therefore not realised. Only fragmented databases exist; for instance, one that includes 360 bridge accidents with a dominance of western bridges,⁵ while the number of worldwide accidents is tenfold or even larger. Only national bodies have made partly comprehensive databases, such as the National Bridge Inventory in the USA, with its 600,000 road bridges. According to that database, over 150,000 bridges are rated structurally deficient or functionally obsolete. Between the years 1989-2009, 600 of those bridges failed.⁶

Over the last century, structures have been planned by engineers through calculations according to formulas. Those formulas are continuously adjusted following new evidence and new kinds of materials. Currently, those formulas are discussed in engineering associations and regularly published and used as the accepted norms.⁷ A calculated carrying capacity is normally multiplied with a security factor. Even with this, nobody can be sure of the durability of a structure, and heavy carriages or trains are often used to test the bearing quality of a new bridge.

With the lack of a worldwide representative database we need to use research made on small samples of accidents. Scheer found that for 536 bridges, 23% of the collapses happened during construction. Imam shows that 34% of the 78 metal bridges he studied collapsed during construction. Imhof found this true for 32% of the 347 bridges he studied, while Lee et al. studied 1,062 American bridges from 1980-2012 and found that only 3% collapsed.

The causes of failure probably change from time to time. According to Imam, for metal bridges the share of accidents were caused by design errors,

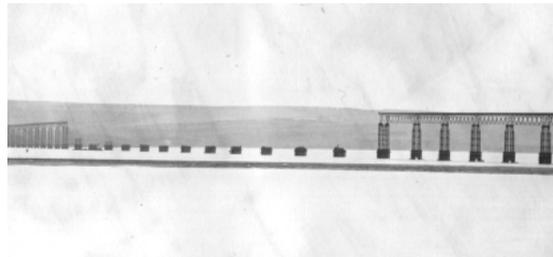


Fig. 3. The Tay Bridge in Scotland opened in 1878 as the largest bridge in the world. Queen Victoria crossed the bridge, and the constructor was knighted by the Queen.

Fig. 4. In 1879 the bridge collapsed during high winter gales and a train with six carriages carrying seventy-five passengers plunged into the water; all people on board were killed.

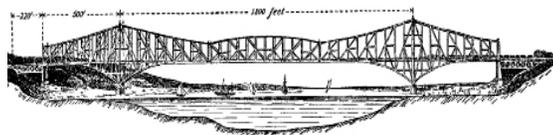


Fig. 5 and 6. The Quebec Bridge should be the longest bridge in the world, but almost finished in 1907 the bridge collapsed and 75 workers were killed.

Fig. 7. The bridge was redesigned and rebuilt. When the central span was being raised into position in 1916, it fell into the river, killing 13 workers. The next year the bridge was completed.



which were reduced after 1970 and then disappeared after 1990. This corresponds with the low percentage of collapsed American bridges in Lee et al. 2013; however, failures reported during service – caused by fatigue, corrosion, and probably a weak inspection and maintenance – was at 94%.

The number of American failures is relatively small. According Lee et al., the number of bridges with failures is 1,062, but this is out of 507,375 total bridges. This number is probably influenced by the fact that the database includes all kind of bridges –the overwhelming majority being small. For instance, only eight culverts out of 133,623 had failures. Of the suspension bridges – often the largest – 10 out of 96 had failures over only 32 years.⁸

From an English study of bridge structures for motorways and trunk roads in Great Britain in 2003, 294 out of 20,995 were found to have failures, and of the failures 13% were caused by design errors.⁹

Types of failures

Natural hazard

This chapter gives an overview of different failures, and I will start with natural hazards caused by extreme situations such as wind, earthquake, and flooding. With increasing climate changes this is an important issue.

Bridges cannot be built to resist all possible conditions, and engineers need to assume a secure limit. For instance, a security limit for a 100-year flood is natural for bridges in service for more than 100 years. Such a bridge should be safe in its lifetime of probably 150 years, but we can't be sure; the occurrence of a 1000-year flood event could be tomorrow.

The Tay Bridge in Scotland is a bridge that failed due to wind in 1879.¹⁰ In some evaluations not only the strong wind but also weak construction was to blame.¹¹ This combination is seen at many similar accidents.



Fig 9. The new built Limsfordsbroen, Aalborg, Denmark, was tested by 48 heavy loaded trucks in 1933.



Fig. 10. The First King's Bridge, Bendigo, Australia did not pass the test in 1901 when two steam rollers tested the construction. Half of the enforced concrete bridge collapsed.

A conclusion is that accidents caused by natural hazards are caused by an underestimation of the power of nature in probable combination with design errors.

Overloading

A bridge is obviously built for a maximum weight within a security span. When this weight is exceeded, the weakest elements can be deformed and make the bridge fail.

The previously mentioned accident in Dixon was this type of bridge failure. Another example is the first cable-stayed bridge in Germany in 1825, which failed during its inaugural celebration when people marched on it to music, resulting in oscillation of the bridge. Again, this bridge had severe weak points in its construction.¹²

External impact

Numerous bridge failures are caused by ships colliding with the structure, derailed trains crashing into the bridge substructure, and accidents with heavy vehicles.

One example is a road bridge in Eschede, Germany in 1998, where a derailed train passing under the bridge hit its foundation and caused more than 100 fatalities. Another example happened in 1975, when a ship collided with a road bridge in Tasmania, and for three months two parts of the island's largest town, Hobart, had no road connection.

Again, better construction principles can decrease the number of this kind of accident. Protective rails can hinder a derailed train from hitting a structure, and crash barriers can hinder vehicles from similar accidents. Bridges in trafficked waters can be protected by artificial reefs. Protection can be made through modest investments.

Fatigue

All materials deteriorate over time. Steel and iron rust, wood can rot, concrete deteriorates through alkali-silica reaction, and through cracks water can reach iron and create corrosion.

Load-bearing capacities can be reduced over the years, leading to disaster. In 2018 the Ponte Morandi bridge in Genoa, Italy, collapsed and killed 43 people. The bridge was built in 1967 but had some construction weaknesses and was in high need of maintenance. The company had offered to retrofit the bridge a few months before the catastrophe, but it was too late.



Fig. 11. The probably most famous bridge accident is the collapse of the Tacoma Narrows Bridge, Washington. Under a storm it began to move vertically and collapsed few months after it opened to traffic in 1940.

Once again, human action could probably have saved this and many other bridges through inspection and renovations.

Human errors

Human errors are often made in the later stages of bridge design. These include errors in the construction phase with the use of poor or the wrong materials, deviation from the original design, incorrect welding methods, and similar issues. Most are discovered by supervisory engineers, so not all result in collapses.

One of the most “unfortunate” bridges in the world was the Quebec bridge, which failed twice. The last time this happened was in 1916, when the last middle span of 5,000 tons was lifted and one of the four suspensions “slipped” during the raising.¹³

This and many other accidents happened under construction. In many circumstances the designer could have made a more robust construction and could have detailed better instructions for the work.

Design errors

At last we are at the most interesting cause of collapses: the poor work of the primary designer. He is often under pressure from investors on time and money. There are examples of everything from bad anchoring, insufficient stiff-

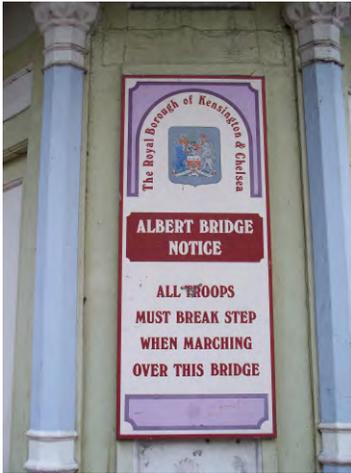


Fig. 12. Marching soldiers have destroyed several bridges because of they were put in oscillations. This sign from Albert Bridge in London is still relevant. The adjacent Millennium Bridge was closed just after its opening in 2000. It took two years to make modifications to eliminate swaying motions in the bridge.

eners, calculation mistakes, to wrong assumptions of ground conditions, and much more.

According Imhof, 21% of all accidents are caused by design errors, although he does caveat that his analysis has a large uncertainty because of many potential factors.¹⁴ Imam gives a similar share of 25%. Lee et al. indicates in their report a much smaller share of only 3%. The report does not discuss how an issue is labelled as a design error; apparently they use information from a database made by others. Scheer has very detailed information on many bridges, but has only counted the faults made in design or dimension for some of the events. For bridges with a known reason for failure in service without an external action the share is 22%.¹⁵

The art of constructing a bridge

Engineering is not an exact science. This is understandably true after reading Henry Petroski's book *To Engineer is Human. The Role of Failure in Successful Design*. More than 1,000 books and articles have cited this popular book, which shows how engineering needs to learn from mistakes. This takes the old adage "Those who cannot remember the past are condemned to repeat it" literally.

But building bridges is more than engineering. The Quebec bridge accident was caused by the "vanity of the designers, which drove them to create a bridge with a middle span length surpassing that of the Firth of Forth Bridge by 27 m".¹⁶ This was close to the conclusion of the Royal Commission that laid the blame for the collapse on two technicians. Alternatively, Kranakis has a total opposite viewpoint: the accident happened because the companies behind it were not organized for as large and innovative a project as the Quebec bridge, with no time for recalculating after the first drawing of the bridge was made, and with no efficient supervision of the work later on.¹⁷

Are record bridges particularly threatened?

New bridges that bring the art of bridge building forward to new frontiers could have weak constructions and therefore be threatened. The greatest challenge to building a bridge is the length of the longest span. A closer look at the large increases in span length among the different design types and the fate of these few bridges can show how they are especially threatened.

Let us start with the UNESCO World Heritage Site-honoured Forth Bridge near Edinburgh in Scotland. The railway bridge was built with 55,000 tons of new Siemens-Martin steel in

Arch bridge (under). Fig. 13. The Upper Steel Arch Bridge at Niagara-Falls USA/Canada was built 1898. Despite a fortification around the abutments the bridge collapsed in the winter 1938.

Arch bridge (over). Fig. 14. The inverted bowstring arch railway Hell Gate Bridge, New York, just after its finish in 1916.

Truss bridge. Fig. 15. The truss railway Forth Bridge, Scotland, opened in 1890 and is still in use.

Suspension bridge. Fig. 16. The road suspension bridge, George Washington Bridge, New York, from 1931. The photo is from 1978. Fig. 17. The road bridge Akashi-Kaikyō Bridge, Kobe, Japan opened in 1998.

Stay bridge. Fig. 18. The road bridge Redbungh Bridge, Newcastle, Great Britain, opened in 1871. Fig. 19. The road bridge Strömsund Bridge, Sweden opened 1956. Fig. 20. The road bridge Pont de Normandie, France, opened in 1995



Fig. 16.



Fig. 17.



Fig. 15.



Fig. 14.



Fig. 13.



Fig. 18.



Fig. 19.



Fig. 20.

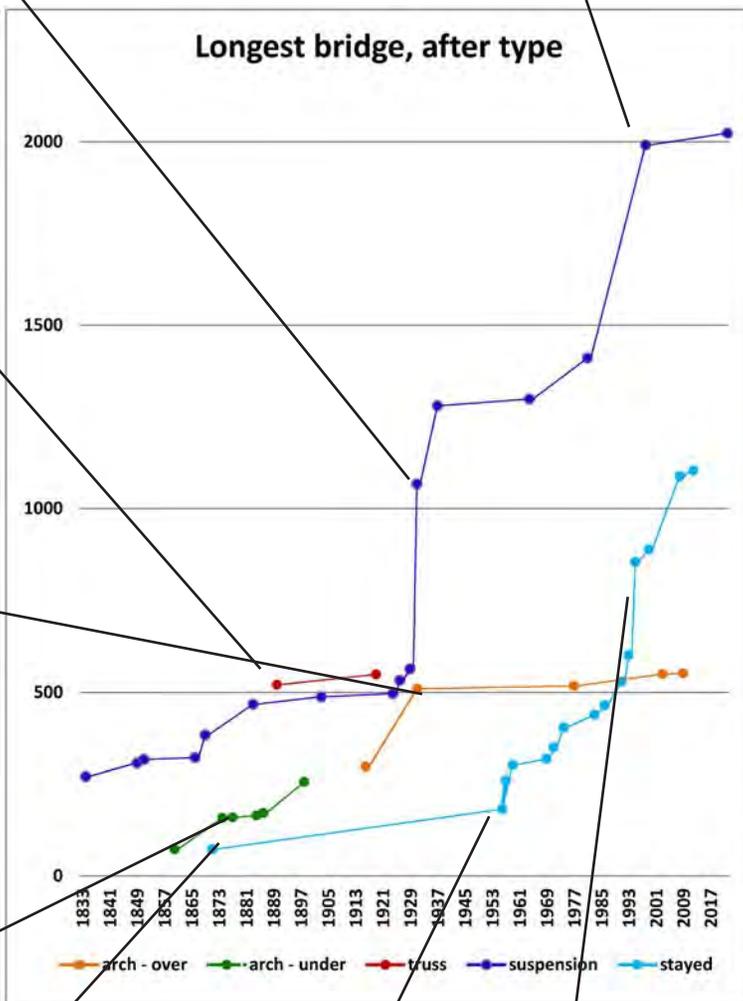




Fig. 21 and 22. On the top photo is the collapsed Chiraja Bridge in 2018, Colombia seen at the right. The failed part was similar to the part of the bridge at left. Below the video pictures from the report on the collapse of a motorway bridge. The cable-stay bridge had a faulty design. Fortunately the accident happened in the lunch time and only ten – not hundreds - died.

1890. It is a truss bridge in a cantilever construction and has self-bearing units. Its longest span is 520m and it is still in use. It is the second largest of its kind in the world, only surpassed by the before-mentioned Quebec Bridge in 1919 with its 549 m span.

Another bridge type is the arch. Arch bridges have long been made of stone or masonry, with span lengths increasing with the use of steel. One important bridge of this type was the Upper Steel Arch Bridge near the Niagara Falls, built in 1898. The length of its span was 256m, almost 40% larger than a similar bridge built 12 years before. The bridge had problems in the winter with ice jams, and in spite of fortification the bridge collapsed in the winter of 1938. The design was unsuccessful in the long run due to its weak points near the water.

Hell Gate Bridge is a railway bridge and still in action. It is an inverted bowstring arch bridge with a span length of 298m. Finished in 1916, it was built of high grade nickel-manganese steel. It took only 15 years before it was exceeded by a bridge with a larger span, Bayonne Bridge, in New York. With its largest span of 510.5m, it exceeded Hell Gate Bridge by 71%. This bridge does not hold the record anymore, but the arches on the new bridges have almost the same length. The bridge is still in action but was rebuilt with a higher deck in concrete so new larger ships can pass under.

For several years around 1920 the truss (the suspension and the arch over bridges) was almost equal in construction of the largest span. This was changed by the George Washington Bridge in New York, inaugurated in 1931, which almost doubled the length of the largest span from the former record holder with its 564m, to an impressive 1,067m. Since then, suspension bridges have had the longest spans. Originally, the bridge had only one deck with six lanes, but in the 1950s was rebuilt with 14 lanes of traffic, with seven in each direction split on two decks.

This impressive bridge held its record until 1998, when the Akashi-Kaikyō Bridge near Kobe in Japan was opened. This six lane road bridge has a span of 1,237m – this time an almost 60% increase in length.

The last type of bridge is self-anchored stayed. The 1871 Redheugh Bridge in North East England had the largest built span of 73 m. This bridge for vehicles and pedestrians was designed by Thomas Bouch, who was also the designer of the first Tay Bridge, which failed in 1879. The Redheugh Bridge lasted longer but its construction was weak and it was replaced by a new bridge in 1901.

More than 50 years passed before the record was beaten, when the Strömsund Bridge in Sweden was opened in 1956 as a road bridge, with a main span of 182m. This was possible due to improved techniques to calculate cable forces throughout the erection period for the cable stayed bridge.¹⁸

The bridge was soon passed by other bridges, and these types of bridges have steadily increased in the span length. One of the record holders is the French Pont de Normandie from 1993, with a span of 856m. It had several new design features, such as the combination of a concrete box girder with a central span of 624m made as a steel box.¹⁹

In summary, some record holder bridges had a short lifetime, but most are still in action. It looks like only the first bridges in the 1800s were in danger.

Lessons

Bridge collapses are described and analysed in reports, and current knowledge is systematically spread and included in a worldwide common knowledge base. The collapses are discussed in journals and congresses, and in education the faulty constructions are used as bad examples in order to find solutions.

But despite of all efforts, as long as bridges have been built there have been failures. Even today bridges under construction still collapse. New ambitions, new materials, and new construction methods give the engineers challenges. Budget cuts, accidents, and wrong or faulty materials can be elements in a chain reaction that result in a collapse. Our new challenge with climate change and more severe weather will bring many bridges down in the years to come.

This study shows that it is not possible to write a world history on bridge accidents at the present time. No databases exists with total or detailed information on collapses. Most accidents from Asia, Africa, and South America are missing. Even information from United States is missing - among them (if a newspaper article is right) 251 railway truss-bridges failing in the USA and Canada between 1877 and 1887.²⁰

Bibliography

- Beal, Alasdair N. (2011): A history of the safety factors. I: *Structural Engineer* 89 (20), s. 20–26.
- Delatte, Norbert (2010): Failure literacy in structural engineering. I: *Engineering Structures* 32 (7), s. 1952–1954.
- Delatte, Norbert & Kevin L. Rens (2002): Forensics and case studies in civil engineering education. State of the art. I: *Journal of Performance of Constructed Facilities* 16 (3), s. 98–109.
- Gimsing, Niels J. & Christos T. Georgakis (2011): *Cable supported bridges. Concept and design*. John Wiley & Sons.
- Imhof, Daniel (2004): *Risk assessment of existing bridge structures*. University of Cambridge.
- Kranakis, Eda (1997): *Constructing a Bridge. An Exploration of Engineering Culture, Design, and Research in Nineteenth-century France and America.*: MIT Press.
- Kranakis, Eda (2004): Fixing the blame. Organizational culture and the Quebec Bridge collapse. I: *Technology and culture* 45 (3), s. 487–518.
- Lee, George C., Satish B. Mohan, Chao Huang & Bastam N. Fard (2013): *A Study of US Bridge Failures (1980-2012)*. (Technical Report MCEER).
- LePatner, Barry B. (2010): *Too big to fall. America's failing infrastructure and the way forward*. New York: Foster Publishing.
- Petroski, Henry (1992): *To engineer is human. The role of failure in successful design*. New York [NY]: Vintage Books.
- Scheer, Joachim (2011): *Failed bridges. Case studies, causes and consequences*. John Wiley & Sons.
- Shave, J. (2003): *A review of bridge assessment failures on the motorway and trunk road network*. Dorking: Highways Agency.
- Åkesson, Björn (2014): *Understanding bridge collapses*. CRC press.

Illustrations

Fig. 1. Photo: Charles Keyes. The Lee County Historical & Genealogical Society and the Loveland Community House, Dixon, IL.

Fig. 2. Photo: Charles Keyes. The Lee County Historical & Genealogical Society and the Loveland Community House, Dixon, IL.

Fig. 3. Tay Bridge, Wikipedia.

Fig. 4. Tay Bridge, Wikipedia.

Fig. 5. 1911 Encyclopædia Britannica, article Bridges.

Fig. 6. Quebec Bridge, Wikipedia.

Fig. 7. Quebec Bridge, Wikipedia.

Fig. 8. Photo by James S. Matthews. City of Vancouver Archives.

Fig. 9. Photo: J. A. Kirkegaard. Aalborg Stadsarkiv.

Fig. 10. University of Melbourne Archives 1964.0012.00260.

Fig. 11. Texas State University.

Fig. 12. Albert Bridge, Wikipedia.

Fig. 13. Unknown lithography 1898.

Fig. 14. The Detroit Publishing Co. collection at the Library of Congress.

Fig. 15. Euchiasmus, Wikipedia.

Fig. 16. Photo: Jack Boucher, Historic American Engineering Record /HAER) collection.

Fig. 17. Photo: Kim Rötzel, Wikipedia.

Fig. 18. Newcastle Libraries.

Fig. 19. Lars Falkdalen Lindahl, Wikipedia.

Fig. 20. Photo: S. Möller, Wikipedia.

Fig. 21. Foto: Modjeski and Masters.

Fig. 22. Foto: Modjeski and Masters.

Endnotes

1 en.wikipedia.org/wiki/Dixon_Bridge_Disaster (2019-09-23).

2 Oswald Rendon-Herrero, cited from Delatte 2009, p. 1952.

3 Delatte 2009, p. 1952 and Delatte and Rens 2002.

4 Ingeniøren 15/3 1974, p. 2-3.

5 Bridge Collapse Database, BridgeForum, University of Cambridge; see Imhof 2004.

6 LePatner 2010, p. 175.

7 Beal 2011.

8 Lee et al. 2013, p. 15.

9 Shave 2003, p. 14.

10 Imhof 2004, p. 16.

11 Åkesson 2008, p. 33-51 and Scheer 2010, p. 122.

12 Scheer 2010, p. 115-116.

13 Scheer 2010, p. 20.

14 Imhof 2004, p. 18.

15 Scheer 2010, p. 85.

16 Scheer 2010, p. 47.

17 Kranakis 2004; see also Kranakis 1997.

18 Gimsing and Georgakis 2011, p. 25-26.

19 Gimsing and Georgakis 2011, p. 66.

20 Sunday Times, Sydney 26/11 1911, p. 5.