Causal Analysis of the Jianzha Yellow River Grand Bridge Collapse Using a Hierarchical Fault Tree



Hou Wenyan[1,*], Zhao Fengxia[1], Guo Zhengting[2]

[1]College of Earthquake Engineering and Architectural Safety, University of Emergency Management, Langfang 065201, China
[2]City Lights Community, Anyang 456500, China

Abstract: Based on the facts established in the official investigation report, this study applies a hierarchical qualitative fault tree analysis to reconstruct the structural failure, management-barrier failures, and casualty consequences of the August 22 major collapse of the temporary cable-stayed fastening system at the Jianzha Yellow River Grand Bridge on the Xining-Chengdu Railway. The results show that the distribution-beam splice simultaneously contained high-strength bolts with substandard mechanical properties and fabrication and installation defects. Their interaction substantially reduced the load-carrying capacity of the joint. The cable force during the second-stage tensioning of No. 4 fastening cable did not exceed the design control value and therefore represented a normal construction condition. Nevertheless, the maximum construction load over the entire erection cycle triggered failure of the already defective joint, which progressed through bolt shear, distribution-beam fracture, failure of the cable-stayed fastening system, and collapse of the arch rib. Material and detailing defects were thus the primary causes, whereas the peak construction load was a failure trigger rather than the root cause. Consecutive failures of procurement, incoming inspection, retesting, fabrication qualification, process inspection, and final acceptance barriers allowed the defects to escape detection. Inadequate control of personnel exposure, warning, and evacuation further increased the casualties. On the basis of these causal paths, this study proposes lifecycle risk controls covering source quality assurance for critical connectors, physical inspection of temporary steelwork, joint acceptance before tensioning, and casualty reduction during high-risk operations. The findings provide a reference for identifying and controlling construction risks in temporary load-bearing systems for long-span arch bridges.

Keywords: Jianzha Yellow River Grand Bridge; Fault Tree Analysis; Temporary Cable-stayed Fastening System; Compound Quality Defects; Management Barriers; Construction Safety

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1 Introduction

During cantilever erection of a long-span steel truss arch bridge, the temporary cable-stayed fastening system, comprising fastening towers, distribution beams, and fastening cables, carries the entire self-weight and construction live load of the unclosed main arch. Although such temporary structures have short service lives, they sustain concentrated loads and complex system-transition conditions. If a critical splice contains material degradation or fabrication and installation defects, a local connection failure can occur even under a permissible construction load and can subsequently cause progressive collapse of the entire system. The August 22 collapse of the Jianzha Yellow River Grand Bridge on the Xining-Chengdu Railway revealed failures in the procurement and inspection of high-strength bolts

*Corresponding author: Hou Wenyan, hhhharpper@163.com

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and temporary steelwork [1]. Applicable fastener and steel-structure standards specify requirements for these components and connections [2-4]. Final physical acceptance of temporary steelwork was ineffective in this accident. Defects passed through procurement, fabrication, and installation before the tensioning that triggered the collapse [1].

Fault tree analysis (FTA) clarifies the logical relationships among basic events, intermediate events, and top events in complex accidents and is widely used in engineering accident investigation and risk assessment [5-7]. Construction-accident causation studies also describe the roles of management decisions and interacting conditions [8-10]. Existing FTA studies of bridge-construction accidents nevertheless have two limitations. First, many assume that a single causal factor acts independently and do not qualitatively examine the interaction between material and detailing defects. Second, structural failure causes and casualty-amplification factors are often combined in one top-event logic, obscuring the distinction between the probability of an accident and the magnitude of its consequences. In addition, the present accident lacks statistical data on component failures and comparative joint-test results, precluding a quantitative probability analysis.

This study uses the accident investigation report issued by the People's Government of Qinghai Province as its sole factual basis [1] and reconstructs a hierarchical fault tree strictly within the direct technical-failure boundary and management-failure facts established in that report. The model has three levels. The first represents the direct failure chain by which compound joint defects caused the overall collapse under the peak construction load. The second traces failures of management barriers that allowed the defects to enter the site and escape multiple acceptance stages. The third separately analyzes casualty amplification caused by personnel exposure and inadequate warning and evacuation. The study is limited to qualitative causal reconstruction; it does not calculate the top-event probability, minimal cut sets, or the importance of basic events. The resulting controls target interruption of risks throughout the temporary-steelwork lifecycle and provide case-based guidance for construction safety on comparable railway bridges.

2 Materials and Methods

2.1 Project Overview

The Jianzha Yellow River Grand Bridge is located at the boundary between Jianzha County and Hualong Hui Autonomous County, Qinghai Province. It is a key control project in Contract XCTJ11 of the Xining-Chengdu Railway. The bridge is 1,596.2 m long, and its main span is a three-span continuous steel truss arch with a configuration of 141 + 366 + 141 m. The arch is divided into 50 erection panels. The main arch was erected by cantilever assembly using arch-mounted derricks without falsework and was supported by a temporary cable-stayed fastening system. The fastening cables were anchored to the arch-rib segments, and all cable forces were transferred through anchor beams to the distribution beams at the tops of the fastening towers.



Figure 1 Cable-stayed buckling system [1]

The distribution beam was the principal welded-steel load-transfer component at the top of each fastening tower. It consisted of several segments connected by bolted splices. All fastening-cable forces were transferred through the high-strength bolts at these splices into the fastening-tower structure, making the splice joint the most vulnerable load-bearing location in the temporary system.

2.2 Accident Sequence and Investigation Findings

At 10:30 on August 21, 2025, the construction crew began the first-stage tensioning of No. 4 fastening cable and reached 67% of the monitored design tension. Second-stage tensioning began at 23:39 that day and was completed at 02:56 on August 22. At 03:01, the cantilevered steel truss arch and associated deck structure on the Xining side suddenly collapsed. The accident killed 13 people, left 3 missing, and caused direct economic losses of approximately CNY 48.86 million.

Based on the official investigation report's documented sequence, forensic testing of recovered components, and computational analysis, the investigation team determined that the converted design shear strength of the bolts involved was 234.5 MPa, 27% below the national standard. Because the threaded portion entered the shear plane, the effective cross-sectional area was 20% smaller than the design value, producing an overall reduction of approximately 41% in bolt capacity. The distribution beam also contained fabrication and installation defects, including oversized holes, field reaming, irregular holes, and missing bolts. After the second-stage tensioning of No. 4 fastening cable, the distribution beam carried the largest load of the entire construction process. The defective bolts failed in shear, leading successively to distribution-beam fracture, overall failure of the cable-stayed fastening system, and bridge collapse [1, 11-13].

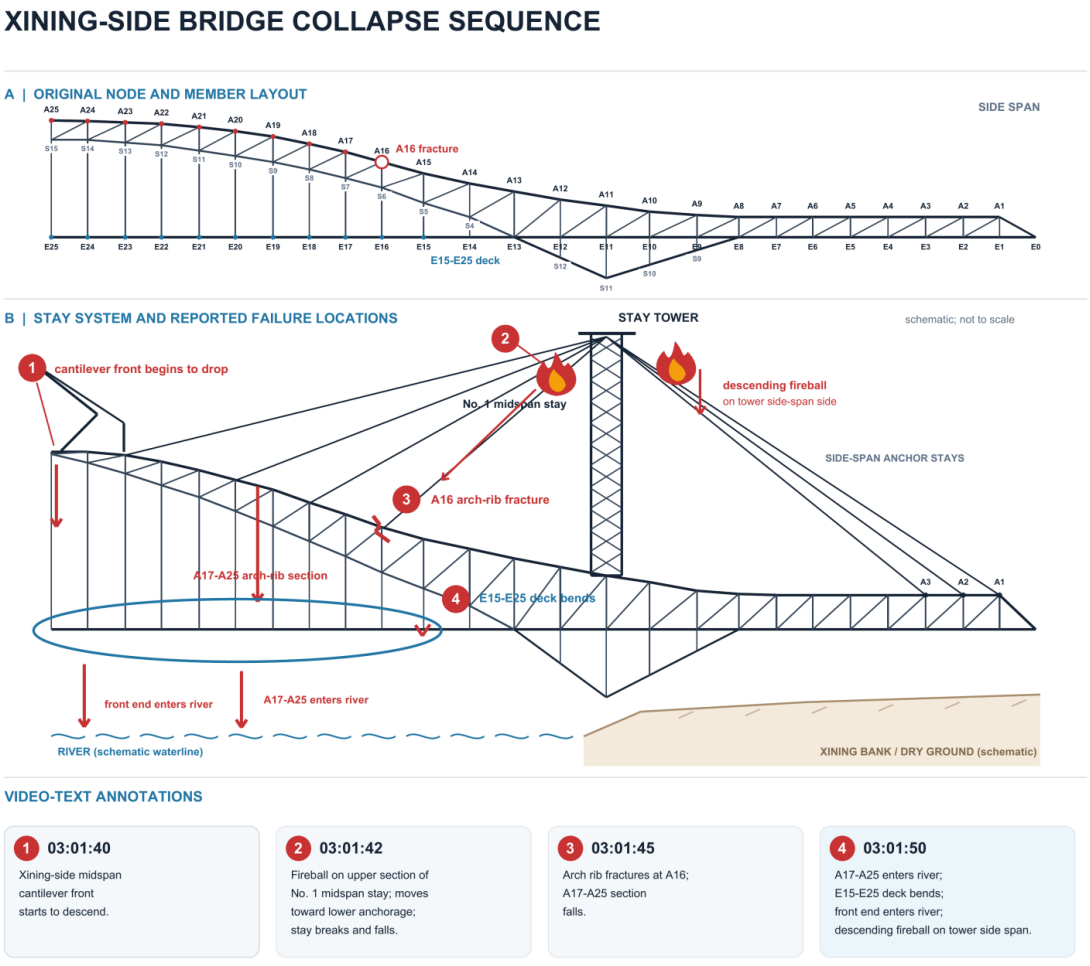


Figure 2 Xining bridge collapse sequence

The parallel verification found that the final tension in No. 4 fastening cable did not exceed the design control value issued by the monitoring organization. The design parameters and incoming inspection results for the fastening towers, fastening cables, anchor beams, anchorages, and wedges complied with the applicable requirements. Accordingly, second-stage tensioning was a normal construction condition that merely exposed pre-existing joint defects; it was neither an independent violation nor an over-tensioning event. Component fractures occurring after the collapse were secondary failures of the system and cannot replace bolt shear at the distribution-beam splice as the initiating failure.

3 Fault Tree Model

3.1 Modeling Boundary and Event Definitions

The data source was the Investigation Report on the August 22 Major Collapse Accident at the Jianzha Yellow River Grand Bridge Construction Project of the Xining-Chengdu Railway, issued by the accident investigation team of the People's Government of Qinghai Province [1]. This study recodes confirmed facts from the report into event logic and does not replace the official findings.

The top event T is defined as the collapse of part of the steel truss arch and deck structure on the Xining side during construction. The model focuses on structural failure and does not use casualties as the top event. The direct failure chain includes insufficient joint capacity, triggering by the maximum normal construction load, and propagation from bolt shear to system collapse. Management events explain how defects formed, entered the site, and escaped interception. Personnel exposure and inadequate warning and evacuation are analyzed separately as casualty-amplification condition D1.

Table 1 Event definitions and roles in the hierarchical fault tree

Symbol	Event	Category/role
T	Collapse of part of the steel truss arch and deck structure on the Xining side	Model top event (final structural-failure outcome)
X1	Substandard high-strength bolts with inadequate mechanical properties at the distribution-beam splice	Material component of compound joint defect A
X2	Fabrication and field-installation defects in the distribution beam (reamed holes, irregular holes, and missing bolts)	Fabrication and installation component of compound joint defect A
X3	Peak construction load generated by second-stage tensioning of No. 4 fastening cable	Structural-failure load trigger
A	Compound quality defect in the distribution-beam joint	Case-specific AND representation of observed X1-X2 co-existence; necessity unverified
E	Bolt shear -> distribution-beam fracture -> fastening-system failure -> arch-rib collapse	Continuous cascading failure path without an independent failure probability
M1-M6	M1 supplier and procurement control failure; M2 incoming material inspection failure; M3 retesting failure; M4 fabrication qualification failure; M5 fabrication and installation process inspection failure; M6 final physical acceptance failure	Multiple safety barriers governing defect entry and escape (not direct necessary conditions for failure)
D1	High personnel exposure in the hazardous zone, inadequate monitoring and warning, and deficient stop-work and evacuation procedures	Casualty-amplification factor outside the top-event logic

3.2 Logical Relationships and Fault Tree

Investigation evidence confirmed that substandard bolts X1 and fabrication and installation defects X2 coexisted and weakened the splice. In this case reconstruction, compound defect A denotes their observed coexistence and is represented by an AND gate. The evidence does not establish that both defects were necessary for collapse under the actual tensioning load:

$$A = X_1 \wedge X_2 \tag{1}$$

In the investigated event, compound joint defects coexisted with the peak load generated by second-stage tensioning. The observed sequence then progressed through bolt

shear, distribution-beam fracture, loss of the fastening system, and collapse:

In the model, compound defect A and peak construction load X3 initiate bolt shear and cascading failure path E, culminating in top event T.

The six management barriers M1-M6 are upstream causes explaining how defects reached the site. Because they occupy a causal level different from the main structural-failure tree, they are represented hierarchically rather than being forced into a single Boolean structure. Barriers M1-M3 specifically control bolt-material defect X1; M4 and M5 mainly control fabrication and installation defect X2; and final physical acceptance M6 can identify both material and detailing defects. All six barriers failed in this accident, allowing both types of defect to enter the load-bearing system without interception [1, 8-10, 14, 15].

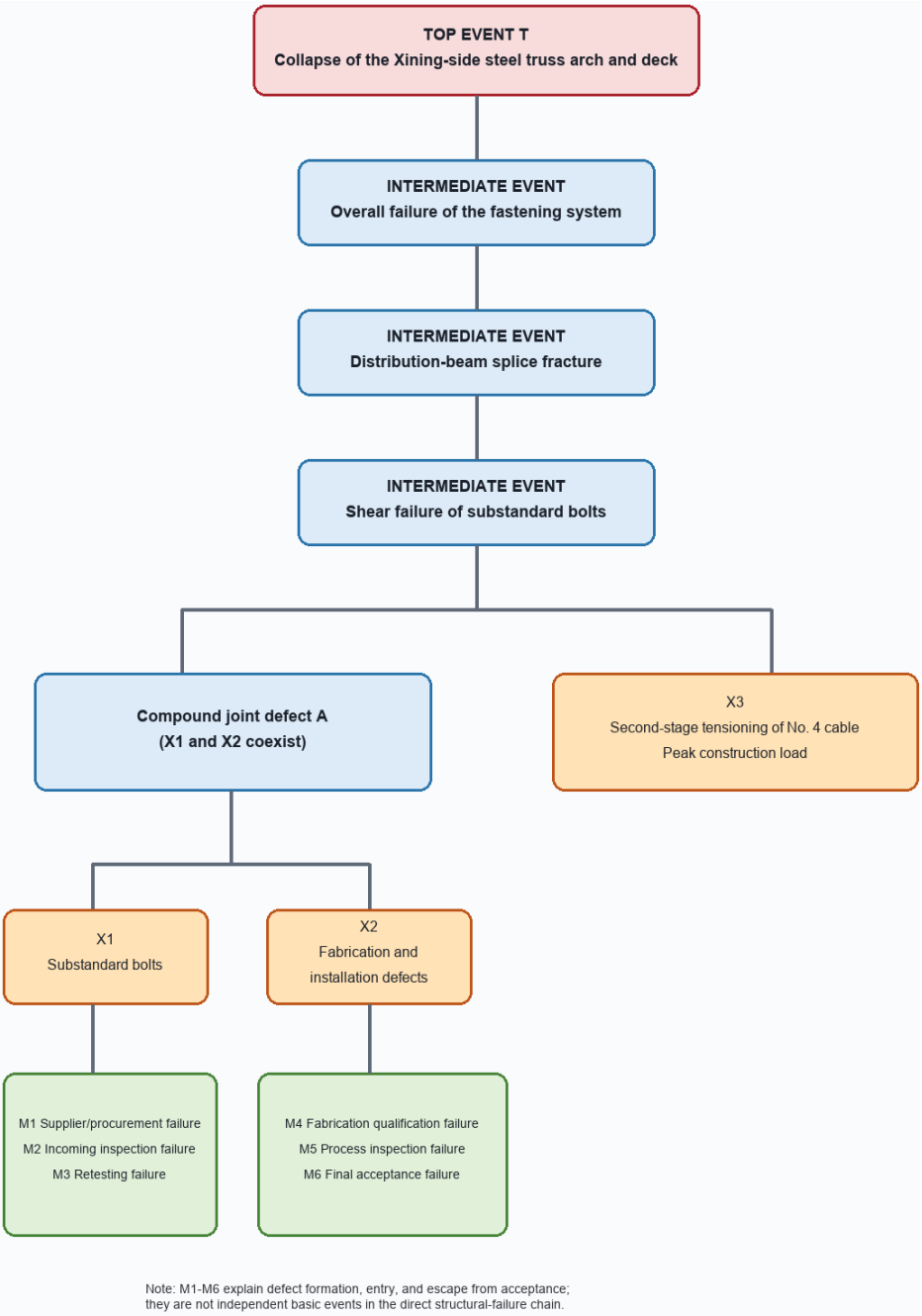


Figure 3 Hierarchical fault tree for the Jianzha Yellow River Grand Bridge accident

3.3 Reconstructed Accident Path and Model Extension

The complete causal path was reconstructed as follows. Failures of bolt procurement, incoming inspection, and retesting allowed substandard bolts X1 to enter the site. Failures of fabrication qualification and process inspection led to reamed holes, missing bolts, and other detailing defects X2 in the distribution beam. The interaction of X1 and X2 created compound joint defect A. Second-stage tensioning of No. 4 fastening cable applied peak construction load X3. The splice bolts failed in shear, and cascading failure then propagated along path E until top event T occurred.

This path identifies targets for risk control at successive stages. The study does not conclude that either X1 or X2 alone was sufficient to cause the accident. Future comparative mechanical testing could examine four conditions: compliant bolts with standard detailing, substandard bolts with standard detailing, compliant bolts with defective detailing, and substandard bolts with defective detailing. Such tests would quantify the separate and interactive effects of the two defect types and support subsequent calculation of minimal cut sets and basic-event importance.

Conventional single-level fault trees often place consequence-related factors, such as warning and evacuation, in parallel with basic structural-failure events, which can incorrectly imply that absent warning is a necessary condition for bridge collapse. The hierarchical decoupled model used here separates the structural-failure tree from the casualty-consequence branch. The main tree explains why the bridge collapsed and supports source-oriented prevention, whereas the independent branch explains why the collapse caused major casualties and supports emergency-loss mitigation. This separation improves the precision of accident-causation analysis.

4 Discussion

4.1 Reduction in Splice-joint Capacity

The official investigation identified two contributors to reduced splice performance: defective bolts and nonconforming fabrication and installation [1].

1. Bolt defects (X1): the converted design shear strength was 27% below the national standard, and nonconforming thread length placed threads within the shear plane, reducing the effective cross-sectional area by 20% [1].
2. Fabrication and installation defects (X2): oversized and irregular holes, field reaming, and missing bolts altered load sharing within the bolt group and further impaired the splice [1].

The reported approximately 41% reduction applies to the load-carrying capacity of the affected bolts, not to the complete splice [1]. The additional reduction in splice capacity caused by X2 was not quantified. Under the peak cable force during second-stage tensioning, the defective bolts failed in shear and the distribution-beam splice fractured [1]. Bolted-connection literature also addresses the roles of bolt properties and joint detailing [11-13].

4.2 Triggering Effect of Second-stage Tensioning

Pages 26-27 of the investigation report state that, according to the theoretical analysis of the cable-stayed fastening system, the distribution beam could resist a maximum tension of 1,884 t from No. 4 fastening cable, whereas the cable itself had a maximum capacity of 3,120 t. The monitoring instruction specified a control tension of 1,200 t. After reviewing tensioning records, jack-calibration certificates, monitoring data, and an independent simulation, the investigation team concluded that the final cable force did not exceed the instructed control value [1]. Second-stage tensioning was therefore a planned construction condition. Its role was to subject the severely defective distribution-beam joint to the maximum load of the construction cycle and thereby trigger failure.

This distinction is important for field control. Monitoring only the tensioning force, while neglecting physical verification of temporary-structure joints, cannot interrupt the failure path at its source. The peak load merely tested and exposed the defect; it was not the root cause of the accident.

4.3 Failure of Management Barriers

The investigation found that material and component defects passed consecutively through procurement, incoming inspection, retesting, fabrication qualification, process inspection, and final acceptance barriers. The bolts involved

were privately selected by the supplier and purchaser before a retrospective order was entered through the procurement platform. Incoming inspection checked mainly specifications, quantities, and packaging and did not effectively verify the original manufacturer's quality certificate. The distribution beams were fabricated by a labor subcontractor lacking the required professional capability and equipment, and technical briefing, process inspection, and dimensional acceptance were ineffective. Final inspection of the fastening-tower distribution-beam system was improperly organized, the inspectors lacked adequate professional competence, and neither raw materials, fabrication records, nor the physical work were effectively verified [1]. These patterns are consistent with established system-based models of construction accident causation, which emphasize interacting task, organizational, and barrier failures [8-10, 14, 15].

The six barriers did not control identical objects. M1 supplier and procurement control, M2 incoming material inspection, and M3 retesting primarily identify and block bolt-material defect X1. M4 fabrication qualification determines whether the fabricator, equipment, and technical conditions are adequate and is therefore the core barrier against fabrication defect X2. M5 process inspection continuously controls hole diameter, hole position, field reaming, and bolt arrangement during fabrication and installation. M6 final physical acceptance comprehensively reviews material certificates, test records, and the completed connection and can identify problems associated with both X1 and X2. Management events should therefore be modeled separately by defect path rather than as one serial prerequisite.

Table 2 Management barriers and observed failures

Management Barrier	Primary Control Object	Normal Control Function	Failure Observed in This Accident	Related Basic Event
M1 Supplier and procurement control	Bolt source and supplier	Ensure compliant procurement channel and product source	Bolts were privately selected before a retrospective order was entered through the procurement platform	X1
M2 Incoming material inspection	Bolt specification, batch, and quality certificate	Verify consistency between the product and its quality documentation	Inspection focused on specification, quantity, and packaging and did not effectively verify the original manufacturer's certificate	X1
M3 Retesting	Bolt mechanical properties	Identify nonconforming materials through retesting	The mechanical-property deficiency of the bolts involved was not effectively detected	X1
M4 Fabrication qualification	Distribution-beam fabrication capability	Ensure adequate fabricator, equipment, and technical conditions	A labor crew lacking the required professional capability and equipment fabricated the beams	X2
M5 Fabrication and installation process inspection	Hole diameter and position, reaming, and missing bolts	Identify and correct fabrication and installation deviations	Reamed holes, irregular holes, missing bolts, and other defects were not effectively corrected	X2
M6 Final physical acceptance	Material and completed-component quality	Perform final review of material, fabrication, and installation quality	Final inspection was improperly organized; professional competence was inadequate; physical quality was not effectively verified	X1, X2

4.4 Factors Amplifying Casualty Consequences

The collapse occurred at night after completion of second-stage tensioning, when many workers remained in the hazardous work zone. The site also lacked standardized procedures for reporting monitoring anomalies, issuing stop-work alarms, evacuating personnel, and verifying headcounts. The interaction of these conditions substantially increased the casualties.

These factors affect only the severity of the accident consequences and do not explain the mechanical origin of the distribution-beam joint shear failure and system collapse. Personnel exposure and inadequate emergency warning and evacuation are therefore represented as consequence-amplification factor D1 outside the top-event logic. This separates two research objectives: the main fault tree explains the mechanism of structural collapse for source-oriented risk prevention, whereas the independent branch explains casualty amplification for emergency-loss mitigation. The separation avoids the common modeling error of conflating collapse causes with casualty causes.

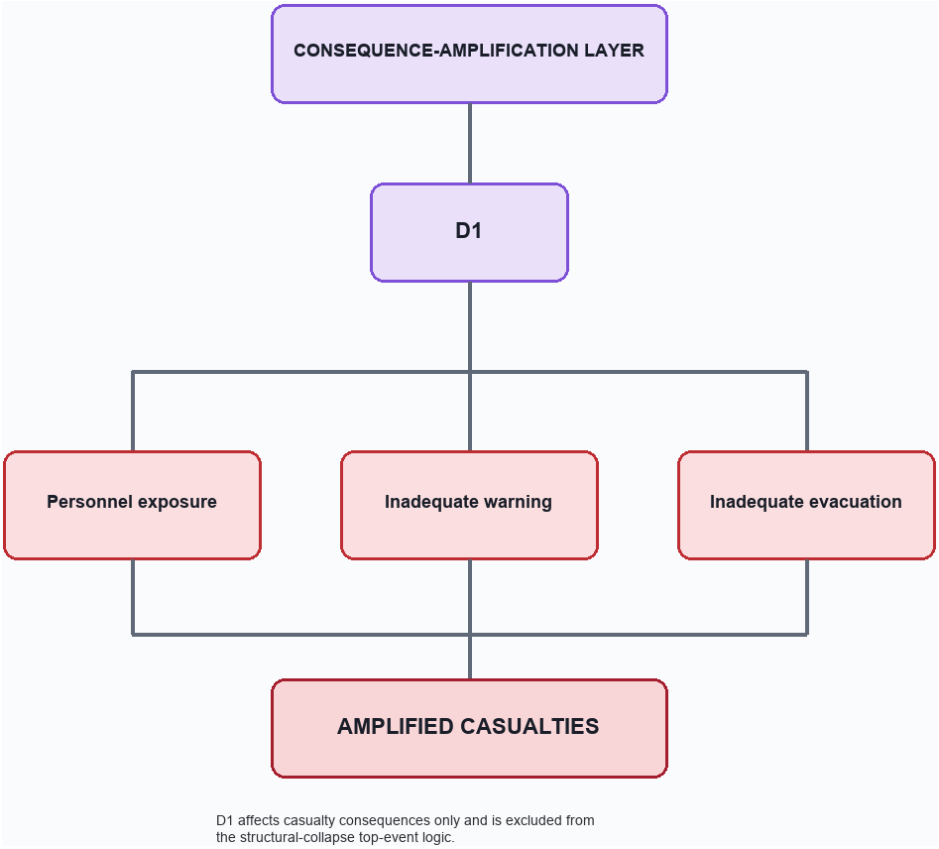


Figure 4 Hierarchical logic model of casualty-amplification factors

5 Lifecycle Risk Control

The hierarchical fault tree indicates that the accident did not result from a single operational error. Material defects and fabrication and installation defects passed through multiple failed management barriers, entered the temporary load-bearing system, and were triggered by the normal peak construction load, producing progressive structural failure. Personnel exposure in the hazardous zone and inadequate emergency response further increased the casualties. Risk control should therefore address four stages: basic defects, process barriers, load triggering, and consequence mitigation. This lifecycle approach shifts emphasis from post-accident response to prior interruption of critical failure paths.

5.1 Strengthen Source Quality Control for Critical Connectors

To address substandard high-strength bolts X1 and failures of barriers M1-M3, high-strength bolts in temporary load-bearing systems should be managed as critical structural components rather than ordinary consumables.

Procurement documents should specify the bolt property class, applicable standard, manufacturer, and batch-traceability requirements. Supplier qualification and procurement procedures should be strictly enforced to prevent products from being privately selected before procurement records are created. Incoming inspection should verify consistency among product specifications, batches, certificates, and physical markings to ensure traceability. Critical load-transfer connectors should be retested as required, and any batch that fails mechanical-property requirements should be quarantined and removed from the site.

Independent quality barriers at procurement, incoming inspection, and retesting can reduce the probability that nonconforming connectors enter the temporary load-bearing system and can block X1 at its source.

5.2 Fabrication and Installation Control

To address fabrication and installation defect X2 and failures of barriers M4 and M5, physical quality control

should cover temporary steelwork from fabricator qualification through field installation.

The professional capability, equipment, and staffing of temporary-steelwork fabricators should first be rigorously reviewed. Critical components should not be fabricated by labor crews lacking the necessary capability. Before fabrication, the designer, contractor, supervisor, and fabricator should jointly conduct a technical briefing that defines critical control indicators for hole diameter and position, plate thickness, welds, and connector arrangement.

Physical inspections during fabrication and installation should verify hole diameter and position, component dimensions, weld quality, bolt quantity, and connection condition. Deviations that affect joint behavior, including reamed holes, irregular holes, and missing bolts, must not be addressed by arbitrary field enlargement or a reduced bolt count. Where adjustment is unavoidable, the designer should perform a technical review and issue a formal change document.

Changing fabrication qualification and process inspection from document review to physical quality control improves the ability of barriers M4 and M5 to intercept detailing defect X2.

5.3 Joint Acceptance Before Tensioning

Because X1, X2, and X3 form a compound failure path, physical acceptance before tensioning should serve as the principal control point for interrupting the accident chain.

Before fastening-cable tensioning, the contractor should systematically review material-retest documents, fabrication records, installation-inspection records, and defect-rectification evidence and should physically self-inspect each distribution-beam splice. The designer, contractor, supervisor, and relevant testing organization should then conduct joint field acceptance, focusing on bolt quantity and condition, hole position and diameter, component dimensions, weld quality, and closure of previously identified quality problems.

Tensioning must not begin if bolts are missing, holes have been enlarged or are irregular, material certificates are inconsistent with the installed components, or quality issues have not been closed. Subsequent tensioning may proceed only after both the physical condition of critical joints and the associated quality records satisfy the requirements.

The purpose of this measure is not to restrict normal tensioning. It is to confirm, before normal peak load X3 is applied, that the temporary load-bearing system contains no inherent quality defect capable of being triggered by that load. The measure therefore interrupts the path from compound joint defect to peak load and joint failure.

5.4 Monitoring and Response

To address personnel exposure, inadequate warning, and deficient evacuation represented by D1, an independent loss-mitigation mechanism should be established without changing the structural-failure tree.

During tensioning, system conversion, and other high-risk operations, hazardous zones should be clearly designated and access by nonessential personnel strictly controlled. A rapid reporting and stop-work mechanism should be established for abnormal monitoring data, including fastening-cable force, fastening-tower displacement, component deformation, and splice-joint anomalies. Relevant work should stop immediately, and personnel should be evacuated and accounted for under predefined procedures whenever abnormal changes occur or critical management staff are absent.

Emergency plans for high-risk tensioning operations should define information flows among the site manager, monitoring staff, workers, and emergency personnel. Regular exercises should test the effectiveness of alarms, work stoppage, evacuation, and headcount procedures.

These measures are intended primarily to reduce casualties after a structural failure and cannot replace source controls for material quality, physical component quality, and pre-tensioning acceptance.

5.5 Establish Lifecycle Control Across the Failure Path

Temporary-steelwork safety management should form a closed lifecycle loop around the critical fault-tree events. Procurement and retesting should block material defect X1; fabrication qualification and process inspection should control detailing defect X2; joint physical acceptance before tensioning should prevent compound X1-X2 defects from being triggered by peak load X3; and exclusion zones and emergency management should reduce casualties after structural failure.

This approach creates a continuous chain of source material control, physical component control, joint acceptance before tensioning, process monitoring, and personnel-exposure control. By mapping each fault-tree path to a specific management stage, it expands risk management beyond construction-load monitoring to include materials, detailing, acceptance, and personnel safety.

6 Conclusions

1) The direct mechanical failure chain was an inherently deficient distribution-beam splice subjected to the peak load of the full construction cycle during second-stage tensioning of No. 4 fastening cable. The high-strength bolts failed by brittle shear, causing distribution-beam fracture, overall failure of the temporary cable-stayed fastening system, and collapse of the cantilevered steel truss arch. The measured tension did not exceed the design control value; the accident cannot therefore be attributed to unlawful over-tensioning.
2) Investigation evidence showed that substandard bolts X1 and fabrication and installation defect X2 jointly constituted compound joint defect A in this accident. Peak construction load X3 during second-stage tensioning triggered joint failure, which propagated along path E into overall collapse. The reconstructed model represents their observed compound path; the available evidence does not establish whether either defect alone would have caused collapse.
3) Six safety barriers covering procurement, incoming inspection, retesting, fabrication control, process inspection, and final acceptance independently intercepted different defects and should be modeled at a level distinct from the direct mechanical failure chain. Four priority controls are full-batch traceability and retesting of load-bearing connectors, measurement-based inspection of distribution-beam fabrication and installation, joint physical acceptance of the fastening-tower distribution-beam system, and a stop-work verification before tensioning.
4) Personnel exposure in the hazardous zone and deficiencies in monitoring, warning, and emergency evacuation affect casualty consequences and should not be included in the logic of the structural-collapse top event. Future research could use joint tests, the four comparative conditions, and basic-event probabilities to verify the gate logic and perform importance and sensitivity analyses.

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