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Cost-effective Resilient Rural Bridges –A Case Study of Masonry Stone Arch Bridges in Kasese District, Western Uganda

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Abstract

Climate change poses an increasing threat to Uganda's road infrastructure, with frequent flooding and bridge washouts making replacement and new constructions costly. This study evaluates the cost-effectiveness and climate resilience of stone arch bridges compared to reinforced concrete alternatives. Using a case study approach comprising site visits, stakeholder interviews, structural, construction and maintenance costs analysis, the research highlights the viability of stone arch bridges for rural settings. Findings reveal that stone arch bridges achieve over 79% to 90% initial construction cost savings for short spans and demand significantly less maintenance of 58% life cycle cost for over 30 years in comparison to Reinforced Concrete bridges. While not ideal for long spans or heavy traffic, they excel in low-load rural environments. Key advantages include long-term durability, reduced lifecycle costs and resilience to climate-related stresses. However, their wider adoption is limited by a shortage of trained professionals and the exclusion of stone arch bridge design in engineering curricula. The study recommends integrating this approach into infrastructure policy to enhance rural connectivity and promote sustainable, climate-resilient road construction in rural Uganda and with comparable contexts.

Keywords: Rural roads, Masonry stone arch bridges, RC bridges, Cost-effective construction, Climate resilience

1. Introduction

The susceptibility of Uganda to climate change has greatly increased the pressure to have resilient and sustainable rural transport infrastructure. The rural population makes up more than 75 percent of the Uganda population and dwells on the road networks to a great extent since it determines movement to the market, health facilities, education establishments and administration centers (Batebe & Nkalubo, 2020). Most of these roads are however unpaved and ill maintained and the crossings of streams are normally underpinned by culverts, timber logs or reinforced concrete (RC) bridges. The latter structures are especially vulnerable to collapsing in rainy seasons when flash floods and the volume of water exceeds its hydraulic capacity (Katumba et al., 2017). This vulnerability has been enhanced by climate change whereby there is increased and severe rainfall particularly in mountainous Districts such as Kasese, Bundibugyo, Kabarole, Ntoroko, Kabale and Mbale. The effects are extensive and destroy infrastructure not only secluding people but also disrupting economic life interfering with the access to the necessary services and postponing the disaster responses as demonstrated in figures 1, 2 and 3.

***Fig. 1**: Eroded Culvert*

***Fig. 2:** Timber Log bridges with Limited Span & Strength*

***Fig. 3:** Timber Bridge at Kyoho, Rwimi River*

The cost incurred by replacing washed out RC bridges or culverts is very high. As mentioned by Ministry of Works and Transport (Larcher et al., 2010), the average cost of constructing or replacing a single-lane short-span RC bridge is between UGX 600million and 1.2 billion, which is prohibitively high to most Local Governments with tight budgets. Also, such structures usually have specialized materials and labor that cannot be produced locally and are expensive. This has created a vicious circle of infrastructure failure and emergency repairs which do not give much long term value or strength.

A promising solution to overcome such challenges is Masonry Stone Arch Bridges (MSABs), which was a technology that was often employed in the colonial age. The structures use local available stone, which is organized in the form of an arch that is efficient in structural and easily adjusts to the local environmental conditions. In contrast to the RC bridges, which require an expensive investment of cement and steel among other materials and local workforce, Masonry Stone Arch Bridges may be made using local materials and labor hence cheaper and more available to the rural Districts (Petts, 2006). The arch structure inherently spreads both live and dead loads to abutments, whereas the open space in the bottom of the structure promotes simpler flow of water, eliminating the chances of blockage and damage caused by floods (Adewole et al., 2019). A visit to colonial stone arch bridges in Uganda in Fort Portal, Jinja and Kasese has shown that numerous of these bridges were built more than 80 years ago and have been in operation since, with little to no maintenance and with consistent exposure to climatic stresses (Mugume & Nabanja, 2018). The specific bridges are not only thematic ones, but they are structurally on the same level in terms of design and materials as compared to those evaluated in this research. Their continued functionality highlights the long-term durability, cost efficiency and suitability of stone arch technology for rural infrastructure. A typical masonry arch is shown in Figure 4 and a constructed stone arch in Figure 5.

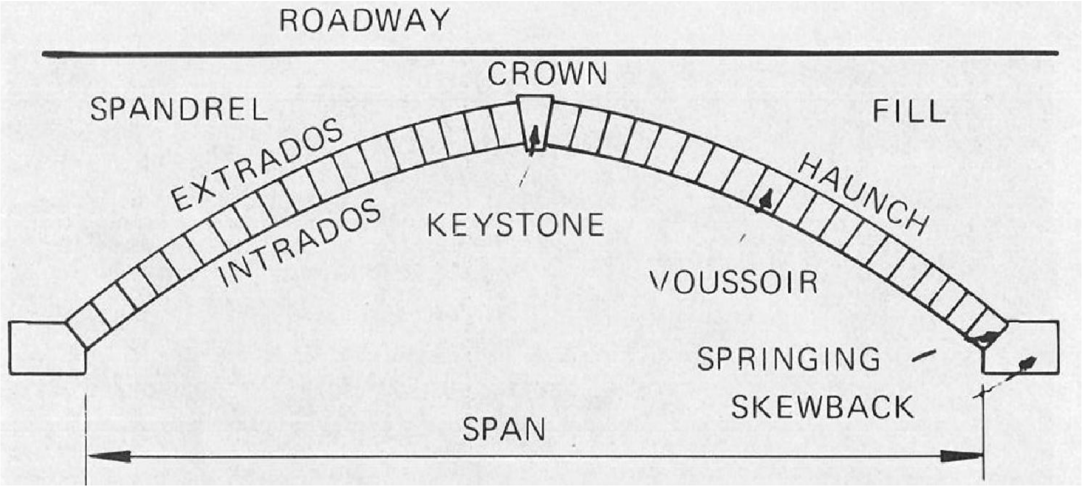


Fig. 4: *Typical Masonry Stone Arch*

Fig. 5: *Kanyampara Tripple Masonry Stone arch culvert, Span 4.2m built in 2012, Mukunyu Sub-county, Kasese District*

In addition to the structural advantages, Masonry Stone Arch Bridges add to the sustainability development and climate change objectives. They help in supporting the local economies by utilizing community members who are artisans, masons and youth in quarrying, shaping and masonry work of the stone, reducing the labor expenses and enhancing the transfer of skills and the creation of jobs (Batebe, 2020). The relatively low carbon footprint is also created by using locally available stone instead of cement manufacture and the transportation of steel, which is in line with the climate obligations of Uganda under the Paris Agreement. Nevertheless, the use is prevented by institutional constraints. Traditional masonry design is much underrepresented in current Engineering Education, and government regulations and purchasing programs still lean towards RC and steel (Mugume & Nabanja, 2018). The proposed research will therefore evaluate the feasibility of Masonry Stone Arch Bridges by conducting a thorough case study on the existing stone arch bridges in Kasese District which is highly prone to floods, there is an abundance of stone and the geography is conducive enough to prove that it is possible to design, build and expand resilient, affordable and context-sensitive infrastructure to suit the transportation requirements of Rural Uganda. The failure of bridge infrastructure in rural Uganda has brought about the element of failure and re-fit. In the period between 2015-2021, more than 400 disasters of climate-related nature were reported in Uganda, 65% of which took place in rural locations (OCHA, 2022). It has been very severe to the Kasese region, where frequent floods have destroyed transport infrastructures and displaced people. Even the 2020 floods have resulted in 24 death victims and the displacement of thousands alone (Uganda Red Cross Society, 2022).

The need to evaluate and advance the utilization of masonry stone arch bridges as an effective low cost approach to bridge building in rural areas in Uganda is therefore important. This could be achieved by undertaking; a comprehensive analysis of cost-benefit of Masonry Stone Arch Bridges and RC Bridges, Evaluating the structural performance of existing Masonry Stone Arch Bridges under flood conditions, Assessing the technical feasibility of applying Masonry Stone Arch Bridges design to other Policies on the national infrastructure and coming up with guidelines on how to incorporate the Masonry Stone Arch Bridges design to the national infrastructure policies.

The rural infrastructure in Uganda is still in a strong trouble, as the quality of roads and bridges remain in poor conditions thus restricting market, medical and educational access. The bridges that are used most frequently are the Reinforced Concrete (RC) bridges that fail very early because of corrosion, bad construction and exposure to flood and scouring. They are expensive since they require imported goods or industrial materials and a skilled workforce hence cannot be used in most rural districts that have very tight budgets. Climate change adds to these weaknesses as there are frequent floods and landslides in places such as Kasese that destroy RCs structures and isolate communities. This has led to the increased awareness of the necessity of more resilient, affordable and sustainable alternatives. The Masonry Stone Arch Brides (MSABs) are a potential solution, since they have been shown to maintain a strong performance over the years and they are also cost-effective. Masonry Stone Arch Bridges that were constructed on large scale during the colonial period continue to serve over 80 years, demonstrating resistance to flooding in flood prone regions where RC bridges tend to be broken down (see Figure 6 showing masonry arch built between 104 AD -106 AD in Spain).

Fig. 6: *Roman stone arch bridge built over the Tagus River at Alcántara, Spain between 104 and 106.AD, Span: 194m*

Their strength lies in the self-supporting arch design, reliance on local stone and elimination of steel reinforcement which reduces both costs and corrosion risks. Studies and pilot projects in Uganda highlight their superior performance, lower lifecycle costs and socio-economic benefits, including job creation and community participation. However, Uganda's current engineering curricula and national design standards favor RC technology, overlooking indigenous solutions like stone arch bridges. Addressing these institutional and policy gaps is essential for integrating Masonry Stone Arch Bridges into Uganda's rural infrastructure strategy, advancing both climate resilience and sustainable development.

2. Methodology

This study employed a mix-methods approach, combining qualitative and quantitative data collection and analysis methods to evaluate the cost-effectiveness and climatic resilience of masonry stone arch bridges in Rural Uganda. The research design consisted of the following components;

2.1 Case Study Selection

2.1.1 Background of the Study Area

Kasese District, situated in the Western region of Uganda, was selected as the central study area owing to its complex topography and well documented history of extreme weather events such as flash floods and landslides. The District lies within the Albertine Rift Valley and is intersected by numerous rivers, including the Nyamwamba and Rwimi rivers which frequently overflow during the rainy season. According to the Uganda National Meteorological Authority (UNMA, 2022), Kasese experiences bi-annual heavy rainfall, with average annual precipitation reaching over 1,200 mm. These hydrological characteristics, coupled with a population exceeding 1,000,000 people (UBOS, 2024), make Kasese an ideal candidate for exploring resilient rural transport solutions like Masonry Stone Arch Bridges (MSABs). The study utilized geospatial mapping tools and secondary data from the Uganda Bureau of Statistics to identify under-served sub-counties where transport disruptions have historically impeded access to markets, schools and healthcare.

Furthermore, the prevalence of naturally available materials and local construction knowledge in Kasese presented unique opportunities for sustainable infrastructure development. Quarry sites in Kilembe and Hima, known for their abundance of hard basalt and metamorphic stones, were assessed for their suitability in stone arch bridge construction (NEMA, 2021). Informal interviews with local masons and engineers were conducted to understand the availability of traditional masonry skills in rural parishes. These contextual factors were crucial in evaluating the feasibility of scaling up Masonry Stone Arch Bridge construction as an alternative to Reinforced Concrete structures. Additionally, socio-economic characteristics such as income levels, primary means of transport and community participation in past infrastructure projects were analyzed to determine how receptive rural communities in Kasese were likely to endorse the proposed bridge technology. By triangulating historical climate data, infrastructure maps and socio-economic indicators, the study laid a solid foundation for assessing how Masonry Stone Arch Bridges could transform rural mobility and resilience in flood-prone Ugandan Districts.

2.1.2 Selection of Bridges

To ensure meaningful evaluation, fifteen (15) existing Masonry Stone Arch Bridges and five (5) Reinforced Concrete within Kasese District were purposefully selected for case study analysis based on clearly defined criteria. The selected Reinforced Concrete bridges include Kaghema bridge (2013) in Kyalhumba S/C, Katumba bridge (2013) in Bugoye sub-county, Nkoko bridge (2013) in Karusandara sub-county constructed in 2012 which have been operational for 12 years (**See Table 4**) and Kyoho bridge (2020) in Bwesumbu Sub-county. Masonry Stone Arch Bridges selected include Kalibu masonry stone arch bridge (2013) in Kilembe S/C, Ndughutu Masonry stone arch bridge(2012) in Bugoye S/C, Kalonge Stone arch bridge(2013) in Kyalhumba S/C and Rwesande masonry stone arch bridge(2021) in Muhokya Sub-county(**See Table 3**).Usage intensity was gauged by examining traffic frequency through community-reported estimates, supplemented by observational data and District records. In Kyalumba S/C, both Reinforced Concrete bridges and Masonry Stone Arch Bridges were constructed by Kasese District Local Government, funded by Belgium technical Cooperation (BTC) through the Kasese Development Poverty Reduction Programme(KDPRP) in the period of 2009-2013.

Technical Supervision was done by Kasese District Department of Works Engineers (Senior Civil Engineer/Road Engineer-Baluku Richard and Assistant Engineer-Alphonse Katswamba) alongside Belgium Technical Cooperation-BTC staff (Project Engineer-Jeff Sozzi Sekimpi and Technical Advisor-H, Steven- BTC). Emphasis was placed on bridges connecting rural trading centers such as those in Kyalhumba, Karusundara, Bugoye and Kilembe where transport continuity is vital for Agricultural trade and access to essential services (Kasese District Development Plan, 2022–2026). Additionally, the selection process considered the proximity of these bridges to perennial water bodies that pose risks of erosion, scouring or sedimentation, ensuring that the chosen structures have been sufficiently tested by natural elements.

Historical construction documents, maintenance logs and budgetary data were sourced from the Kasese District Engineering Department and collaborating civil society organizations. These records helped to quantify original construction costs, frequency of maintenance and any major rehabilitation undertaken over time. Community feedback was also solicited through structured interviews with bridge users and local leaders, helping assess user satisfaction and perceptions of structural safety. This grassroots perspective was to enrich the technical evaluation and provide insights into the social acceptability and utility of Masonry Stone Arch Bridges in Rural communities. Additionally, visual inspections were employed to evaluate the condition of structural components such as voussoirs, spandrels, abutments and wing walls. Special focus was placed on identifying common failure modes and maintenance challenges, particularly in relation to water channeling and vegetation encroachment. This comprehensive analysis of selected Masonry Stone Arch Bridges served as a replicable model for future studies and inform recommendations on mainstreaming stone masonry bridge technology in Uganda's rural infrastructure policy framework.

2.2 Data Collection

2.2.1 Cost Analysis

Data was gathered on the bridge's initial construction costs and maintenance records. A detailed cost analysis was conducted to compare the construction costs of masonry stone arch bridges with reinforced concrete bridges. The analysis included; initial construction costs and maintenance costs. Life-cycle cost modeling over a 30-year horizon, Net Present Value calculations and Sensitivity Analysis for material price fluctuations were done.

2.2.2 Analytical Structural Analysis

Analytical Structural analysis was done to evaluate the load carrying capacities of both types of bridges. Colonial Era MEXE method was used for analysis of Masonry stone arch bridges while well codified RC bridges used relevant British standards and Roads and Bridges Design Manual, 2010, MoWT. Limit state design verification was done on both types of bridges.

2.2.3 Visual Structural Assessment:

All twenty bridges underwent detailed visual inspections to document signs of material degradation, structural distress (cracking, spalling, joint displacement) and water seepage and vegetation encroachment.

2.2.4 Stakeholder Interviews:

Semi-structured interviews were conducted with District Engineers, site foremen, local residents and road users to collect qualitative data on construction practices, perceived durability, frequency of maintenance and climate-related damage like heavy floods.

2.2.5 Sampling strategy.

A total of fifteen stone arch bridges and five reinforced concrete bridges constructed in Kasese District were included in the study. The bridges were selected based on their location, design and construction type.

2.2.6 Research Instruments:

Interview Guide: semi-structured interview guides were developed to gather data from stakeholders

Cost analysis templates: templates were developed to gather data on construction costs and maintenance records

Durability Assessment checklists: Checklists were developed to evaluate the condition and durability of bridges

2.3 Analytical Structural Modelling Samples (See Appendix 1 for details)

2.3.1 MEXE Method for analyzing Load carrying capacity of Masonry Stone Arch Bridges Scope

The test was concerned with the strength of the ARCH BARREL ONLY. The spandrel wall, wing wall, foundations and others may have some influence on the strength of the bridge. The modified MEXE can also be applied to determine the carrying capacity of arches spanning up to 18m, although above 12m spans, will be rather conservative than other methods. The test of the arch barrel has been modified in accordance with the procedure prescribed by Military Load Classification (of Civil Bridges) by the Reconnaissance and Correlation Methods, MEXE May 1963 (10.2.1). This is a procedure that is founded on the outcome of the previous experience and has been observed to produce acceptable outcomes to the diversity of vehicles that are in compliance with the Road Vehicles (Authorized Weight) Regulations.

Provisional Assessment

The Provisional Axle Loading (PAL) is calculated using reference to formulae in which the arch span L and the sum of the crown thickness (d + h) (barrel and fill) are calculated. The Provisional Axle Loading (PAL) can be acquired by replacing values of (d + h) and L in the following equation:

$$PAL = \frac{740\,(d+h)^2}{L^{1.3}} \quad \text{or 70, whichever is less}$$

The Modified Axle Load is given by

$$\text{MODIFIED AXLE LOAD} = F_{sr} \cdot F_p \cdot F_m \cdot F_j \cdot F_{cM} \cdot PAL$$

Calculating internal forces of the arch under action of vertical loads

The equation below gives the cross sectional position of the arch and the center line of the arch. The cross sectional angle ϕ, which is the angle produced by the tangent to the arch's center line and the axis of abscissa, changes with the cross sectional position of the arch.

$$y = \frac{4h}{l^2}x(l-x)$$

The slope of a section of the arch may be determined by the first derivative:

$\tan\phi = \frac{dy}{dx}$ thus sinϕ, cosϕ of the angle ϕ may be determined as well

Shearing force (shear), axial force and bending moment are examples of internal force components across a random segment of an arch.

The method of sections is used to compute internal forces. The following Figure 7 will be used to develop the formulas for computing internal forces across an arbitrary cross section D of an arch under vertical loads.

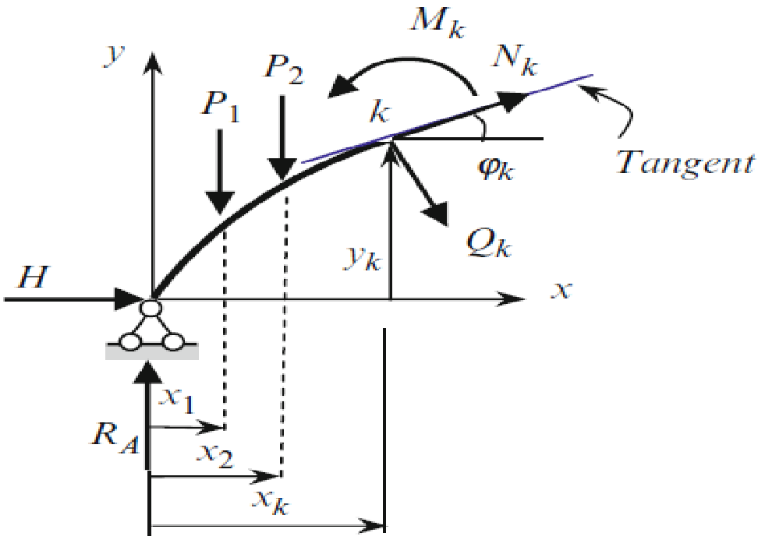


***Fig.** 7: Diagram for Forces*

In any section k of the arch, the following internal forces arise: the Bending Moment Mk, Shear Qk and Axial Force Nk

The internal forces acting on cross section k can be calculated based on the left or right part of the free body diagram of the arch. The left half of the arch is convenient to use.

The research used a limited state design approach by following the Design Manual of Roads and Bridges (DMRB VOL.2 SEC 2 PART 14 BD 91/04) to assess the structural performance of Masonry Stone Arch Bridges (MSABs) under design load conditions. Both Ultimate Limit State (ULS) and Serviceability Limit State (SLS) were checked during the analysis as the questions were whether the arch ring is stable, durable and serviceable in the course of its lifecycle. In the case of the ULS, the principle checks consisted in ensuring that compressive forces in the arch ring were not greater than the allowable limit determined by the following expression: $N \leq 0.4bfk(h-2e)$, where parameters such as masonry strength (fk = 15 N/mm^2), arch thickness (h = 600 mm) and arch ring width (b = 1000 mm) were based on standardized values and site-specific measurements.

2.3.2 Analytical Structural analysis of Reinforced Concrete Bridges (Kyoho Bridge) (see Appendix 1 for details)

For comparative purposes, RC bridges were analyzed as follows;

2.3.2.1 Design of Kyoho Bridge (14m span)

The bridge deck slab (Figure 8), bridge beams, abutment and foundation base/footing are the main components that were developed. The existing temporary foot bridge was replaced by a reinforced concrete bridge with a span of 14 meters and a height of 5 meters.

For a 50-year design life, the RC bridge was built to support a maximum of 40 tonnes and to allow for the greatest amount of storm water, river base flow water and large rocks to pass through. The following are the various parts of the Kyoho Reinforced Concrete Bridge that have been designed:

Consider bridge span layout as shown in Figure 8 below;

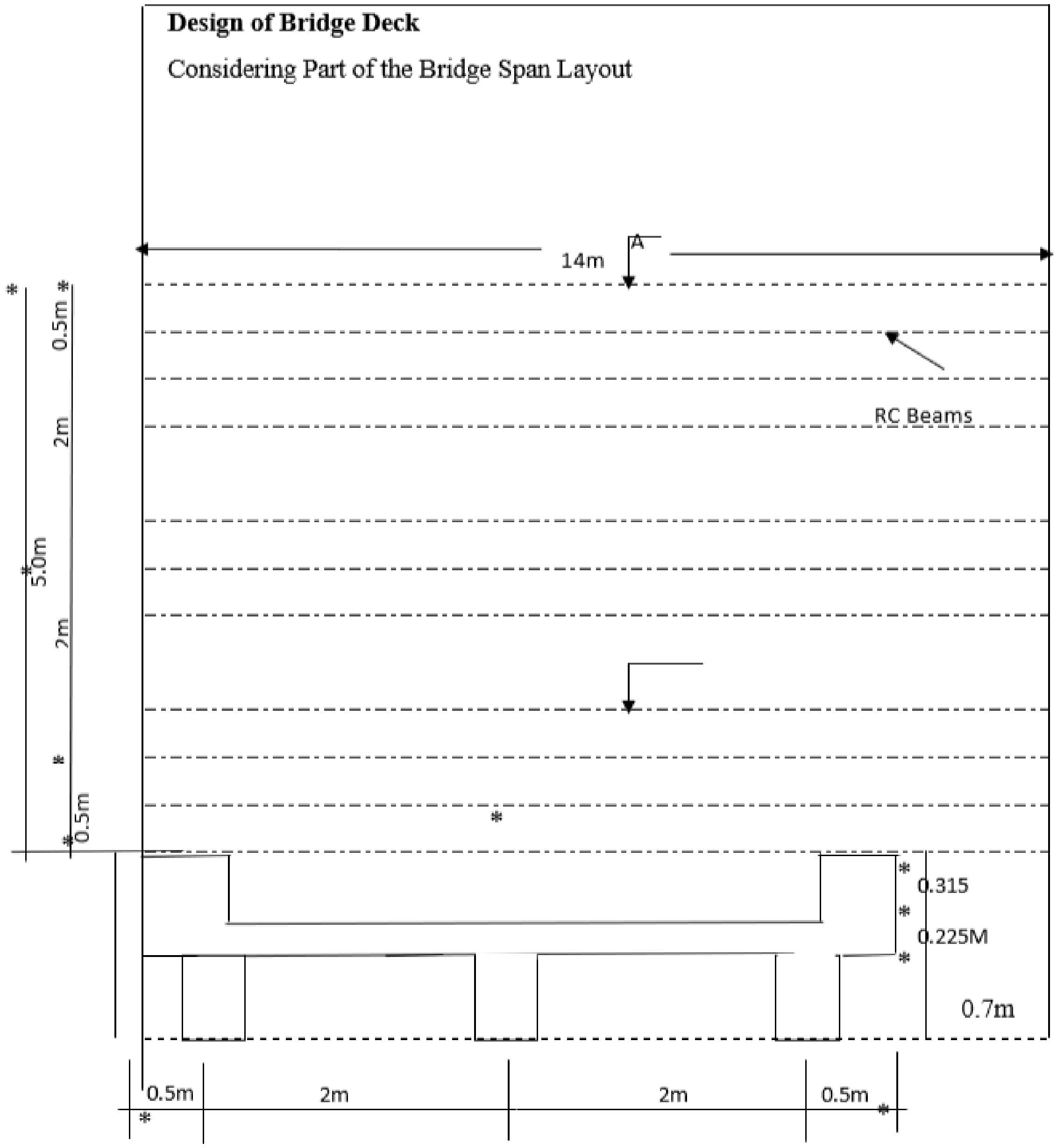


Fig. 8: Sketch for Loading of Kyoho Plan Layout

Deck Slab

I designed the Reinforced Concrete Deck Slab with a Span of 5 m wide, slab thickness (h) of 225mm and effective depth (d) of 169mm resting on three Beams with the Middle Beam fixed at the centre of 2.5m and running through 14m long. I Designed Reinforced Concrete Bridge Deck Slab in accordance with MoWT Bridge Design 2010(Table 13), where assumptions where as follows; 1) Density of reinforced concrete=24KN/M^3 , 2) Density of Asphalt Concrete =23KN/M^3, 3) Type HA Uniformly Distributed Load (UDL) over a loaded length> 30m = 30KN/M , 4) Knife Edge Load(K.E.L) per notional lane of 3M = 120KN per notional lane. The Design was also based on Road Note 9(Page 10): Design Manual for Small Bridges-Page 10, BS 8500 –Part 1(Tables A.1, A.3 and A.5), BS 5400: Part 1,2 &4) and Mosley 2007(Table 6.10,Pages,63,65,134 & 397)

I estimated slab thickness and effective depth from;

Span/d Ratio for a continuous slab =26

Effective depth, $d \geq \frac{2000}{26} = 76.92mm$

Slab thickness h=d + cover $+\frac{\emptyset}{2}h = 76.92 + 50 + \frac{12}{2} = 132.92mm$

$d = 225 - 50 - \frac{12}{2} = 169mm$

I used slab thickness, **h=225mm** and effective depth, **d=169mm**

I considered Dead Loading from Reinforced Concrete (RC) Deck, Asphalt Paving, Parapets and Guard rails which totaled to 11.23KN/M. In accordance with Road Note 9(Page 10), I used HA loading since Traffic Volume was Low for purposes of determining Imposed Loads-I (Live Loads) as follows; HA was in accordance with BS 5400: Part 2:1978, MoWT BDM 2010

HA (UDL) = 30 KN/M of notional lane

HA (KEL) = 120/3 = 40KN/M

Total HA in transverse direction = 30+40 = 70KN/M

From the excel sheets and in accordance with Subframe Analysis to BS8110:1997,

I considered Maximum moment=**40.5KNm from Combination 1 ULS** which was greater than other combinations.

I provided Reinforcement Designs against Bending, Shear stress, compressive stress, tensile stress, Strain and Crack control (Mosley 2007)

I used design factors as shown in **Table 1** below and in accordance with MoWT Bridge Design Manual (BDM) 2010.

Table 1: Partial Safety Factors for Design of Deck Slab Calculations

	Combination 1		**Combination 3**	
Load	SLS	ULS	SLS	ULS
Concrete	1.0	1.15	1.0	1.15
Superimposed Dead	1.2	1.75	1.2	1.75
HA Alone	1.2	1.5	1.0	1.25
Temperature Difference	-	-	0.8	1.0*

Source: *MoWT Bridge Design Manual (BDM) 2010, Table 1)*

Bridge Beam (14m Single Span)

I designed the Reinforced Concrete 14m **Single span** Beam supported on two Reinforced Concrete Abutments. I based the Design on BS 8500: Part 1:(A .Table A.1)1990: Concrete Specification, Mosley 2007 (Table 6.10, pages 134, 177, 188), MoWT Bridge Design Manual(BDM) 2010(Table 1, 13)and BS 5400: Part 2, 4:, ICE Manual of Bridge Engineering, Page 192, 290) I sized the Beam in accordance with Minimum Span/ Effective Depth ratio for simply supported Beam = 20

$dmin = \frac{Span}{20} = \frac{14,000}{20} = 700mm,$ I took

$h = d + cover\ 1\ \frac{\phi}{2} + \phi$ links

$$= 700 + 50 + \frac{32}{2} + 10 = 776mm$$

I took, $h = slab\ thickness + 700$

i.e., $h = 225 + 700 = 925mm$

$$d = 925 - 50 - \frac{32}{2} - 10 = 849mm$$

I determined effective depth of Beam, **d=849mm** and height, **h=925mm**

The loading on the beam was as shown in **Figure 9** below

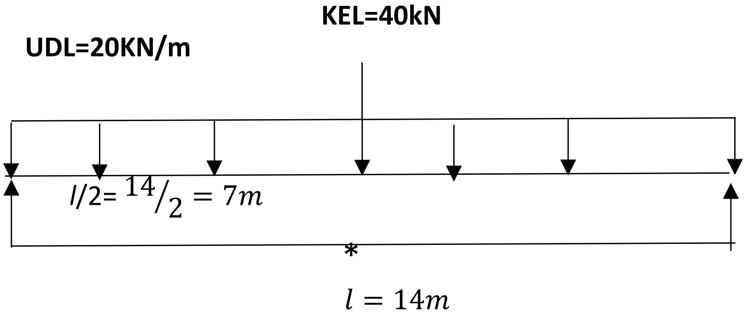


***Fig. 9:** Sketch for Loading of Kyoho Bridge Beam*

The deck rests on 3No. Identical beams with two end edge beams and one middle beam. I designed Beam in accordance with BS 8500 Part 1 (Table A.1), Mosley 2007, MoWT Bridge Manual 2010, Table 13. I considered a Bridge Beam Span of 14m long and 400mm width.

I determined Dead Loads (D) UDL from RC Slab(D_{11}=6.48KN/M), RC beams(Dtot=18.6KN/M), Asphalt surfacing(D_2=1.725KN/M). I determined imposed from HA as Ia =10KN/M and Knife Edge Load (KEL) as I_b =40KN.

I used partial safety factors for Kyoho beam calculations as shown in Table 2 below;

Table 2: Partial Safety Factors for Beam Calculations

Load	**Combination 1**		**Combination 3**	
	SLS	ULS	SLS	ULS
Dead load	1.0	1.15	1.0	1.15
Superimposed Dead Load	1.2	1.75	1.2	1.75
HA Load Alone	1.2	1.5	1.0	1.25
Effect of Temp. difference	-	-	0.8	1.0

***Source:** MoWT Bridge Design Manual (BDM) 2010, Cl4.4.1, Table 1*

The structural analysis for both Kalibu Masonry Stone arch bridge and Kyoho load carrying capacities of 40 tons shows compliance with ultimate limit state designs with relevant factors of safety. RC bridge designs are more codified, detailed and referenced than Masonry stone arch bridge designs.

This study employed mix-methods approach, combining qualitative and quantitative data collection and analysis methods to evaluate the climatic resilience and cost-effectiveness of masonry stone arch bridges in Rural Uganda.

3. Results and Discussion

3.1 Cost Comparison

The analysis found that there were significant cost savings in the construction and maintenance of Masonry Stone Arch Bridges (MSABs) as compared to the reinforced concrete (RC) bridge. To be more exact, it is estimated that Masonry Stone Arch Bridges will need 79-90 percent (Table 6) lower initial capital costs, especially in rural locations where it is easy to find natural stone and not expensive labor force with traditional masonry skills. As compared to RC bridges that require the use of imported or industrial cement, steel reinforcement and multifaceted formwork, Masonry Stone Arch Bridges are made using materials that are found within the country and thus, there is low transportation and procurement expenses. The analysis also found that Masonry Stone Arch Bridges have lower lifetime cost with saving of 58 percent (Table 9) as they have minimal maintenance needs, the maintenance needs are limited to repairing mortar joints and trimming vegetation compared to RC bridges whose maintenance needs are usually expensive, namely resurfacing, reinforcement corrosion treatment or structural retrofitting. There was a thorough lifecycle cost analysis that segregated the expenditures, over a 30 year period, to actual infrastructure planning schedule (Table 8). Visualization of results was done by using comparative bar graphs, cost breakdown table and projected savings chart to make stakeholders aware of the differences in capital, operation and maintenance costs as presented in Tables 3,4,5,6,7,8,9 and Figures 10,11,12,13, 14 below:

Table 3: *List of Masonry Stone Arch Bridge in Kasese District*

Bridge Name	Funding Source	Span (m)	Year	Construction Cost (UGX)	Inflation	Adjusted cost (2025	Maintenance	Total Cost (UGX)	Cost per m Span (UGX)	Cost Index (UGX/m²)
Kalonge	Kasese DLC	8	2013	22,451,545	5%	40,319,749	0	40,319,749	5,039,969	1,119,993
Kakone	Kasese DLC	4	2012	20,545,300	5%	38,741,227	0	38,741,227	5,136,325	2,152,290
Ndughutu	Kasese DLC	8	2012	22,600,000	5%	42,615,671	0	42,615,671	2,825,000	1,183,769
Bikone	Kasese DLC	5	2012	15,700,000	5%	29,604,692	0	29,604,692	3,140,000	1,315,764
Nyangerek	Kasese DLC	8	2021	119,953,500	5%	145,804,229	0	145,804,229	14,994,188	4,050,117
Kinyabisik	Kasese DLC	6	2017	72,000,000	5%	106,376,792	0	106,376,792	12,000,000	3,939,881
Kisinga-K	MoWT	8	2020	102,198,120	5%	130,433,576	0	130,433,576	12,774,765	3,623,155
Kisinga-K	MoWT	12	2020	166,242,856	5%	212,172,692	0	212,172,692	13,853,571	3,929,124
Rwenzori I	Kasese DLC	8	2018	141,760,480	5%	199,471,231	0	199,471,231	17,720,060	5,540,868
Rwensand	Kasese DLC	7	2013	-	5%	-	0	-	-	-
Rwesande	Kasese DLC	14	2021	159,035,800	5%	193,309,009	0	193,309,009	11,359,700	3,068,397
Kanyamba	Kasese DLC	5	2012	5,987,240	5%	11,289,834	0	11,289,834	1,197,448	501,770
Kalibu	Kasese DLC	8	2012	20,263,000	5%	38,208,909	0	38,208,909	2,532,875	1,061,359
Kitakena	Kasese DLC	9	2022	270,039,945	5%	312,604,991	0	312,604,991	30,004,438	7,718,642
Isule	Kasese DLC	3.6	2012	4,100,000	5%	7,731,161	0	7,731,161	1,138,889	477,232

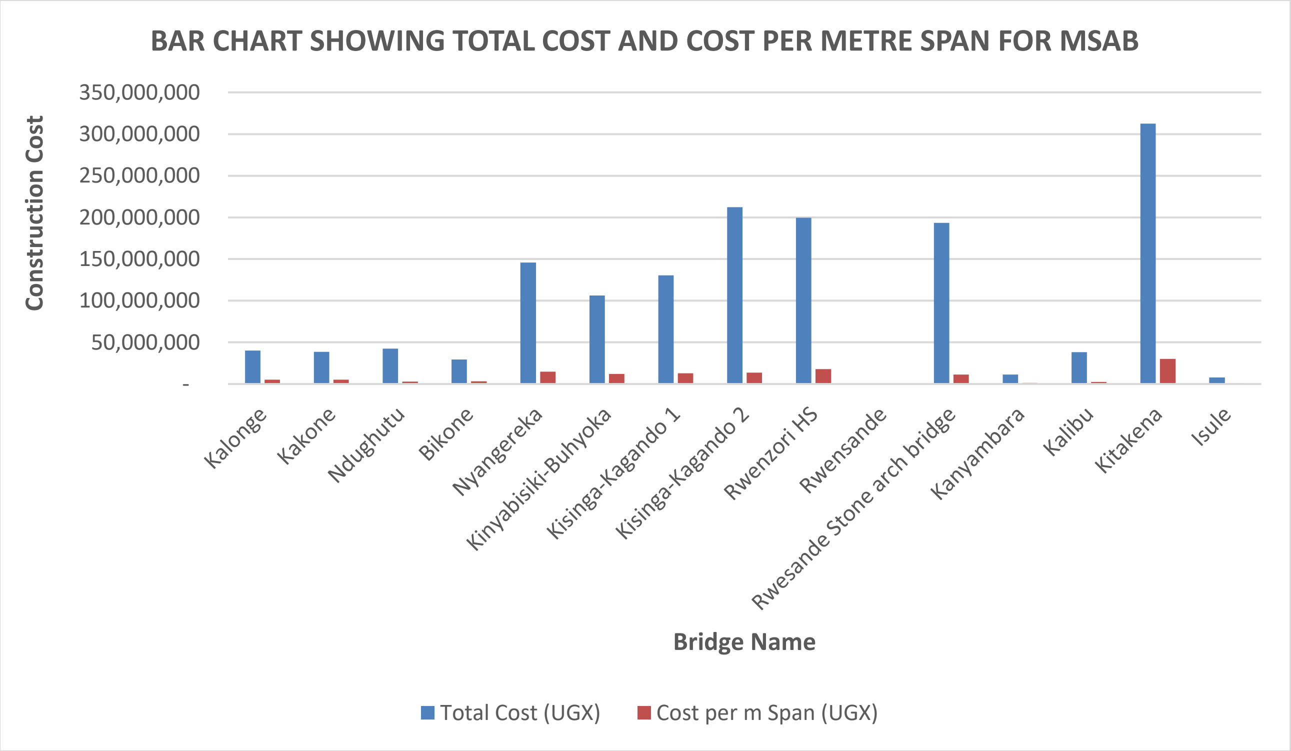


Fig. 10: *Adjusted Costs for Masonry Stone arch bridges Chart*

Table 4: *List of Reinforced Concrete Bridges in Kasese District*

Bridge Name	Funding	Span	Year	Construction Cost (UGX)	Inflation rate	Adjusted cost (2025 UGX)	Maintenance	Total Cost (UGX)	Cost per m Span (UGX)	Cost Index (UGX/m^2)
Kaghema	Kasese I	13	2013	300,000,000	5%	538,756,898	0	538,756,898	41,442,838	9,209,520
Nkoko	Kasese I	13	2013	398,000,000	5%	714,750,818	0	714,750,818	54,980,832	12,217,963
Katumba	Kasese I	14	2013	356,000,000	5%	639,324,852	0	639,324,852	45,666,061	10,148,014
Kanyamunyu	Kasese I	3.5	2013	128,000,000	5%	229,869,610	0	229,869,610	65,677,031	14,594,896
Kyoho	Kasese I	14	2020	754,000,000	5%	962,316,298	0	962,316,298	68,736,878	15,274,862

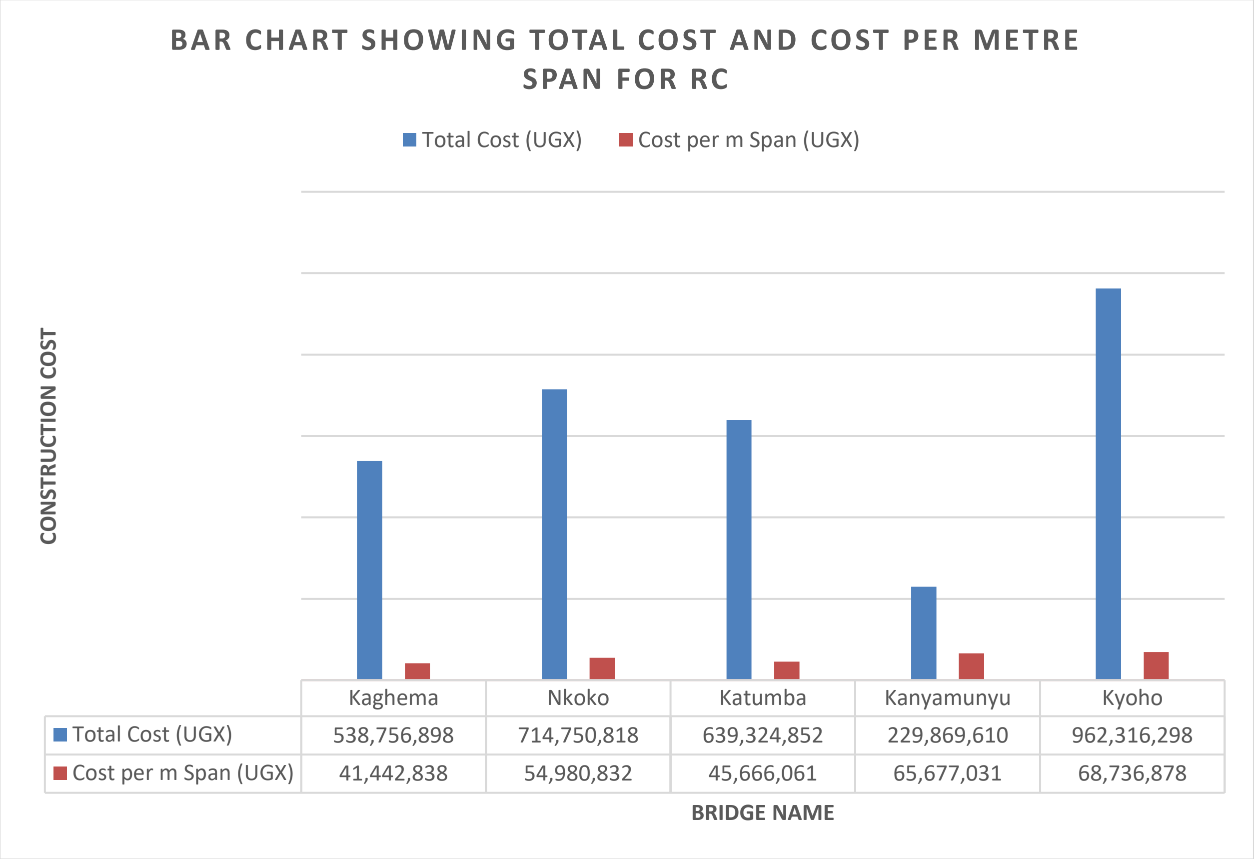
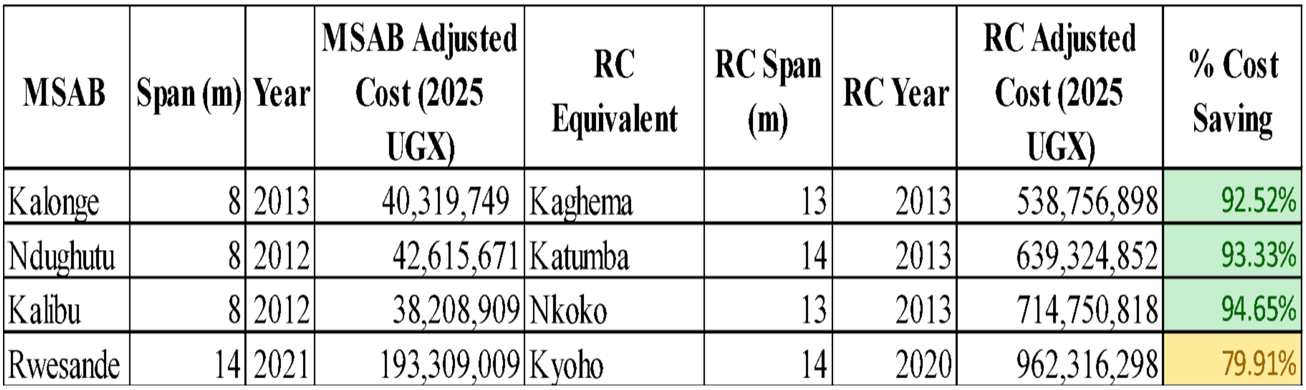


Fig. 11: *Adjusted Cost for RC Bridges Chart*

Table 5: Summary of Cost Analysis of both types of bridges

Metric	MSAB	RC
Count (No. of Bridges)	15	5
Mean Total Cost (UGX)	100,578,918	617,003,695
Median Total Cost (UGX)	42,615,671	639,324,852
Min Total Cost (UGX)	7,731,161	229,869,610
Max Total Cost (UGX)	312,604,991	962,316,298
Std. Dev. (Total Cost)	94,569,914	267,062,207
Mean Cost per m Span (UGX)	8,914,482	55,300,728
Std. Dev. Cost per m Span	8,254,874	11,970,464
Mean Cost Index (UGX/m²)	2,645,491	12,289,051
Std. Dev. Cost Index	2,168,460	2,660,103
Coefficient of Variation (%)	94	43

Table 6: *Cost Saving Analysis*



MSAB	Span (m)	Year	MSAB Adjusted Cost (2025 UGX)	RC Equivalent	RC Span (m)	RC Year	RC Adjusted Cost (2025 UGX)	% Cost Saving
Kalonge	8	2013	40,319,749	Kaghema	13	2013	538,756,898	92.52%
Ndughutu	8	2012	42,615,671	Katumba	14	2013	639,324,852	93.33%
Kalibu	8	2012	38,208,909	Nkoko	13	2013	714,750,818	94.65%
Rwesande	14	2021	193,309,009	Kyoho	14	2020	962,316,298	79.91%

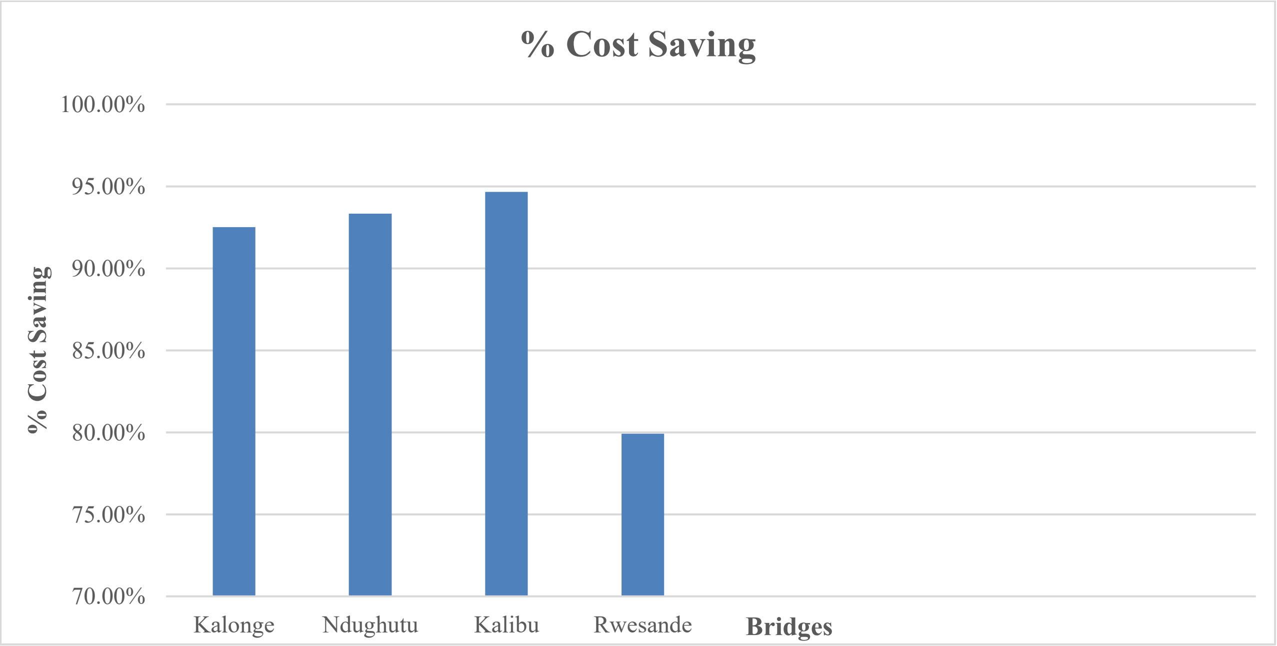
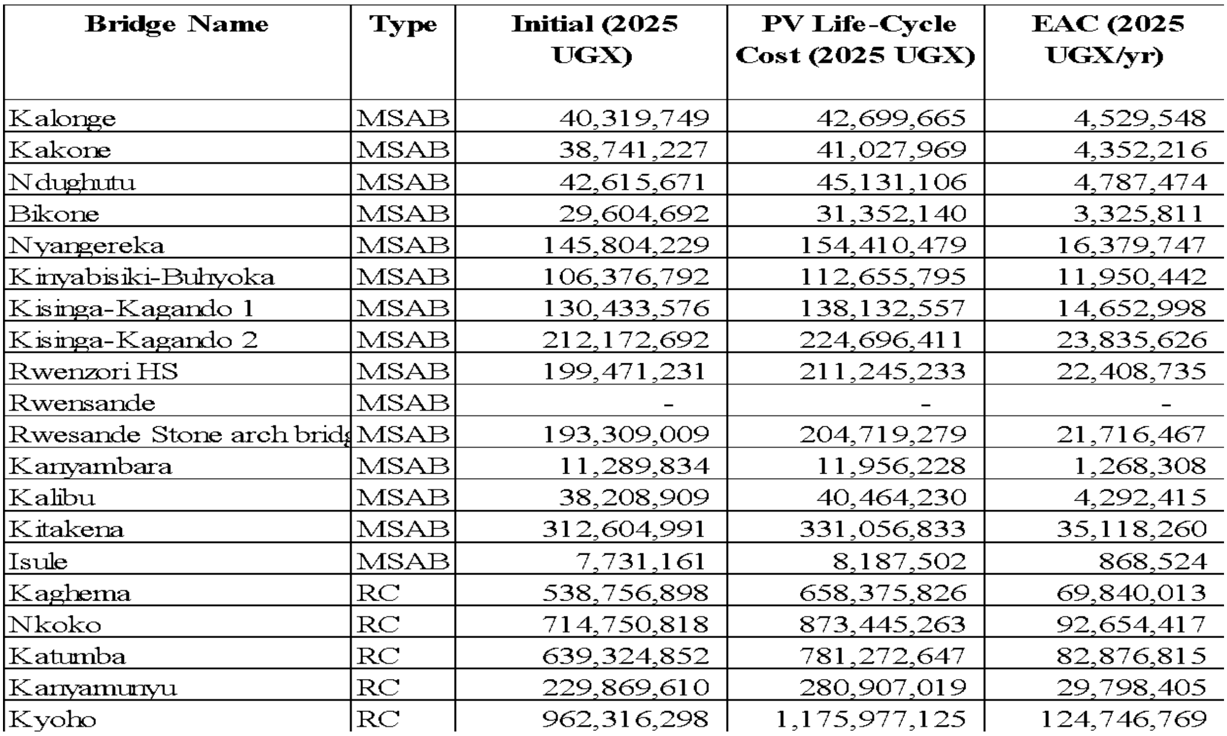


Fig. 12: *Cost Saving Chart*

Table 7: *Summary for Life Cycle Cost Analysis Considerations*

Parameters	Value
Base Year	2025
Inflation Rate (for adjustment)	0.05
Real Discount Rate	0.1
Analysis Horizon (years)	30
MSAB Routine (% of initial per year)	0.005
MSAB Event (Year=20, % of initial)	0.08
RC Routine (% of Initial per year)	0.01
RC Events (5y 5%, 10y 15%, 15y 5%, 20y 15%, 25y 5%)	As stated

Table 8: *Life Cycle Cost Analysis*



Bridge Name	Type	Initial (2025 UGX)	PV Life-Cycle Cost (2025 UGX)	EAC (2025 UGX/yr)
Kalonge	MSAB	40,319,749	42,699,665	4,529,548
Kakone	MSAB	38,741,227	41,027,969	4,352,216
Ndughutu	MSAB	42,615,671	45,131,106	4,787,474
Bikone	MSAB	29,604,692	31,352,140	3,325,811
Nyangereka	MSAB	145,804,229	154,410,479	16,379,747
Kinyabisiki-Buhyoka	MSAB	106,376,792	112,655,795	11,950,442
Kisinga-Kagando 1	MSAB	130,433,576	138,132,557	14,652,998
Kisinga-Kagando 2	MSAB	212,172,692	224,696,411	23,835,626
Rwenzori HS	MSAB	199,471,231	211,245,233	22,408,735
Rwensande	MSAB	-	-	-
Rwesande Stone arch brid	MSAB	193,309,009	204,719,279	21,716,467
Kanyambara	MSAB	11,289,834	11,956,228	1,268,308
Kalibu	MSAB	38,208,909	40,464,230	4,292,415
Kitakena	MSAB	312,604,991	331,056,833	35,118,260
Isule	MSAB	7,731,161	8,187,502	868,524
Kaghema	RC	538,756,898	658,375,826	69,840,013
Nkoko	RC	714,750,818	873,445,263	92,654,417
Katumba	RC	639,324,852	781,272,647	82,876,815
Kanyamunyu	RC	229,869,610	280,907,019	29,798,405
Kyoho	RC	962,316,298	1,175,977,125	124,746,769

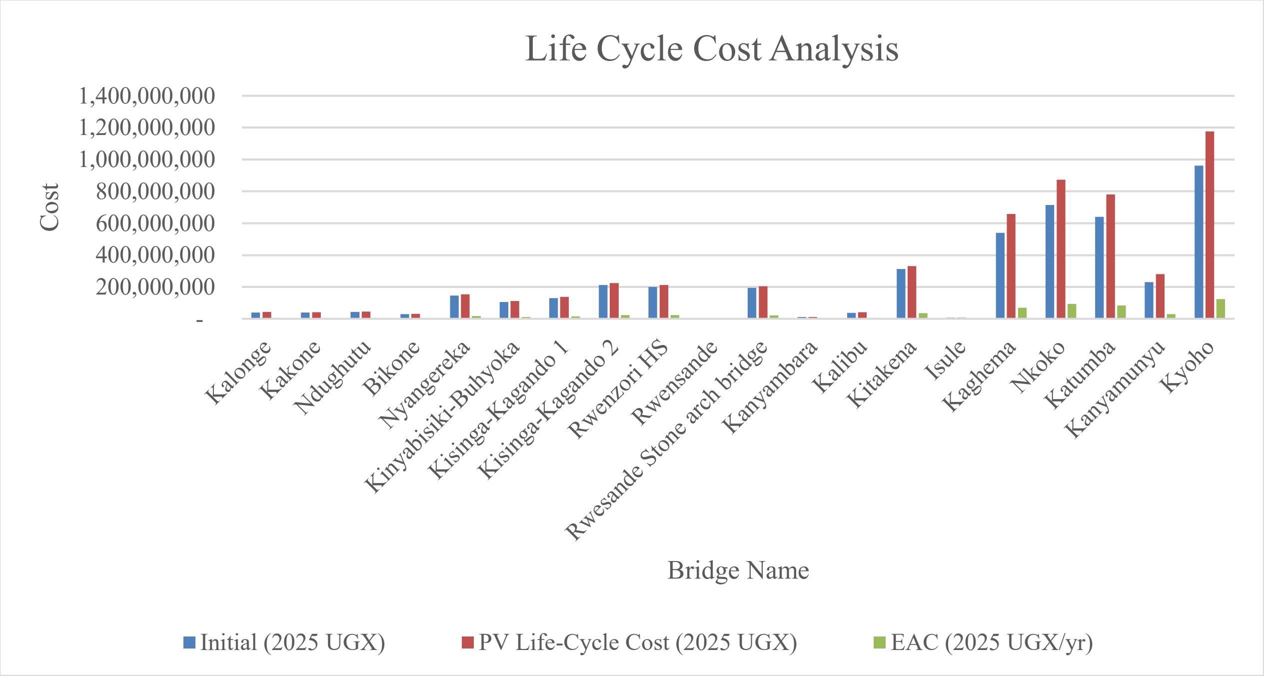


Fig. 13: Present Value life and EAC Chart

Table 9: *Cost Sensitivity Analysis*

Scenario	**Discount Rate**	**MSAB Maint Multiplier**	**RC Maint Multiplier**	**Total PV LCC (MSAB, 2025 UGX)**	**Total PV LCC (RC, 2025 UGX)**	**Combined PV LCC (2025 UGX)**	**% Saving (MSAB)**
Base Case	0.1	1	1	1,597,735,426	3,769,977,880	5,367,713,306	58
Discount -2%	0.08	1	1	1,619,500,770	3,922,080,327	5,541,581,097	59
Discount +2%	0.12	1	1	1,581,959,419	3,655,269,213	5,237,228,631	57
MSAB Maint +20%	0.1	1.2	1	1,615,545,758	3,769,977,880	5,385,523,638	57
MSAB Maint -20%	0.1	0.8	1	1,579,925,093	3,769,977,880	5,349,902,973	58
RC Maint +20%	0.1	1	1.2	1,597,735,426	3,906,969,761	5,504,705,187	59
RC Maint -20%	0.1	1	0.8	1,597,735,426	3,632,985,999	5,230,721,425	56

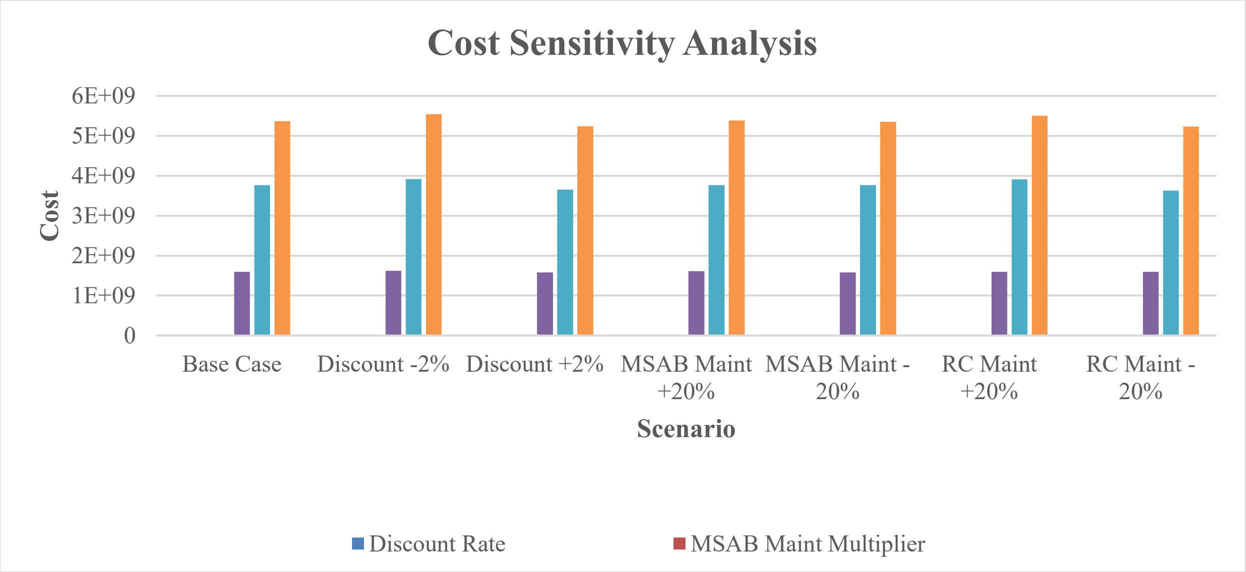


Fig. 14: Cost Sensitivity Analysis Chart

3.2 Discussion

Masonry Stone Arch Bridges (MSABs) offer a significant financial advantage over the initial and long-term expenses, according to a cost comparison between MSABs and Reinforced Concrete (RC) bridges adjusted to 2025 values (Tables 3 and 4) based on a 5% annual escalation factor. The RC bridges were nearly twice as expensive at UGX 3.77 billion (Table 9) with low variability (CV = 43%) due to standardized construction processes, despite the fact that site conditions, span variation and workmanship caused high variability (CV = 94, Table 5) in the initial cost of Masonry Stone Arch Bridges of UGX 1.60 billion. IThe Masonry Stone Arch Bridges consistently shown reduced cost indices in terms of unit span and deck area, hence bolstering its cost-effectiveness. As demonstrated in Table 9, this benefit was further highlighted in the Life-Cycle Cost Analysis (LCCA) over 30 years, discounted at 10%, with Masonry Stone Arch Bridges maintaining their initial cost level of UGX 1.60 billion in contrast to RC bridges' higher costs of UGX 3.77 billion over the course of their entire service life. This makes MSABs roughly 58% less expensive over the course of their service life. Because Masonry Stone Arch Bridges required less maintenance than RC bridges, which required costly and frequent repairs, Equivalent Annual expenses (EAC) again confirmed that Masonry Stone Arch Bridges had much lower yearly expenses (Table 8). Sensitivity analysis showed that while the life-cycle cost of RC bridges was significantly impacted by changes in the discount rate and maintenance costs, the costs of Masonry Stone Arch Bridges were relatively stable, supporting their long-term durability and financial sustainability (Table 9). Generally speaking, Masonry Stone Arch Bridges are a more sustainable investment in rural infrastructure as they not only have lower initial costs but also exhibit great cost leadership throughout the course of the service.

3.3 Key Findings

According to the results, Masonry Stone Arch Bridges will always be less expensive than RC bridges during initial construction, saving between 79% and 90% (Table 6) and throughout the course of their lengthy lifespan, saving 58% on overall expenses, as indicated in Table 9. In contrast to the average initial construction cost of Ugx 600 million RC bridges, as indicated in Table 5, the analysis reported an average initial construction cost of Ugx 100 million for Masonry Stone Arch Bridge. This result is in line with research by Larcher et al. (2010), which estimated that it may cost between UGX 600 million and UGX 1.2 billion to rebuild a small-span RC bridge in rural Uganda. Even after accounting for future maintenance and different economic situations during the sensitivity analysis, as indicated in Table 9, the Present Value Life-Cycle Cost (PV LCC) of Masonry Stone Arch Bridges at this level was substantially cheaper than that of RC bridges. The long-term financial performance of RC bridges can be significantly impacted by changes in discount rates and future maintenance cost increases, in addition to their higher initial cost.

Although the cost of the Masonry Stone Arch Bridge is less predictable because of its larger coefficient of variation, it is better positioned to maintain a significant financial lead since it saves a significant amount of money on construction when compared to RC bridges. This suggests that standardizing the design and construction methods of Masonry Stone Arch Bridges might increase cost predictability without compromising the bridges' financial benefits. RC bridges, on the other hand, are more accurate in calculating initial costs, but having a long-term financial load makes them more vulnerable to changes in the economy and maintenance schedule. Masonry stone arch bridges and culverts are generally less expensive than traditional reinforcement concrete bridges and culverts. Over a 30-year lifespan, RC bridges have low maintenance costs and initial construction cost savings of over 79 percent (Table 6) and life-cycle cost savings of over 58 percent (Table 9).

3.4 Structural Performance, Cost Efficiency and Durability of MSABs

According to the study, Masonry Stone Arch Bridges (MSABs) are a far more cost-effective alternative to reinforced concrete (RC) bridges in rural and flood-prone areas of Uganda. The average MSAB construction cost for short-span bridges (Table 3) was between UGX 40 million and UGX 312 million, whereas the average cost for RC equivalents (Table 4) with similar span and functionality was between UGX 229 million and UGX 962 million. All 15 MSABs that were evaluated had single spans between 4 and 14 meters, carriageway widths between 3 and 4.5 meters, and were constructed for light to moderate traffic loads (Load Class B), which typically included pedestrians, motorbikes and small cars, in accordance with Uganda's Rural Road Standards. Analytical structural evaluation confirmed that the arch shape effectively distributed loads with minimal stress concentrations and all bridges met elastic and ultimate limit state performance criteria. Visual inspections conducted as part of durability testing revealed sufficient material integrity for continued use. Historical records and stakeholder interviews provided additional evidence of long-term durability, demonstrating that all of the masonry stone arch bridges that had been in use for over 12 years were still functional and in need of no significant repairs. However, after 10 to 15 years, the selected RC bridges showed clear signs of deterioration due to scouring, concrete cracking, and corrosion of the reinforcement. These results demonstrate that Masonry Stone Arch Bridges function very well over time and are a cost-effective option for rural infrastructure, particularly in places with little funding, material or maintenance resources.

3.5 Hydraulic Structural Performance and Durability

The structural reliability and long-term durability of the Masonry Stone Arch Bridges were assessed by field testing. It was anticipated that the findings would demonstrate how well Masonry Stone Arch Bridges performed in the face of environmental pressures such flash floods, soil erosion, and sedimentation, which are common in Uganda's rural areas. Mugume and Nabanja (2018) assert that the inherent capacity of the arch shape to efficiently distribute compressive loads lessens localized stress, enhances resistance to foundation scouring and disapproves common causes of failure for RC culverts and slab bridges. Visual inspections of the selected Masonry Stone Arch Bridges focused on indicators including joint deterioration, vegetation intrusion, water seepage and structural deformation. According to the study, Masonry Stone Arch Bridges only need minor maintenance and show few signs of deterioration even after ten or more years.

These results showed that RC bridges usually fail too quickly due to inadequate drainage and material deterioration, but Masonry Stone Arch Bridges are suitable for areas that are susceptible to erosion and floods.

4. Conclusion and Recommendation

The research evidence illustrates the practicability and economic viability of masonry stone arch bridge technology in the Rural Uganda environment, particularly for short span bridge construction. The research evidence makes it apparent that the masonry stone arch bridge technology is an attractive alternative to the conventional reinforced concrete bridge technology in terms of flood resilience, sustainability, viability, and costs associated with rural infrastructural development in flood-prone regions in Rural Uganda. Masonry Stone Arch Bridges, in their relatively simpler structural configurations, emphasized their adaptability to smaller river bridge constructions in irregular terrain with the possibility for artisans' employment in multi-arch systems without loss of structural integrity. Experiential design comparison notes from such demonstration sites establish that while the Kalibu stone arch bridge and Kyoho RC bridge act as points of valid references in terms of their size and flood resilience, similar smaller structures in their valid applications establish the adaptability and reproducibility of Masonry Stone Arch Bridge technology in a more appropriate way, albeit according to specific site-related challenges for improvement in artisan involvements in their construction. Altogether, Masonry Stone Arch Bridges/Culvert Technologies in comparison with conventional reinforced concrete bridge/Culverts in general could indeed be more economical in the construction costs with an over 79% saving initial construction, and also over 58% saving in life cycle costs with much reduced maintenance costs over their 30-year lifespan in comparison with their RC bridges.

The proposed recommendations should be adopted by the Ministry of Works and Transport in Uganda, the District Engineering Departments and the other development partners should incorporate Masonry Stone Arch Bridges (MSABs) into the rural infrastructure plans in light of their demonstrated cost-effectiveness, durability and social acceptability in hillside and flood-vulnerable areas. Some key recommendations would be to incorporate stone arches into the national manuals for bridge design, to establish design standards for these structures, in addition to providing training for engineers, contractors and masons on their construction. Masonry Stone Arch Bridge construction practices would also need to be incorporated into civil engineering studies, in addition to ensuring that procurement systems allow for execution by the District Local Governments together with the communities they serve. Other areas requiring research would be construction innovations, durability testing, in addition to performance standards in collaboration with new technology such as BIM-building information modeling systems.

In order to realize the potential offered by masonry stone arch bridges, it is recommended that the following policies be implemented:

- **Inclusion in National Design Manuals:** The bridge design manuals in Uganda should incorporate masonry stone arch typologies into the techno-classes considered for the construction of rural infrastructure projects in the country.
- **Further Research:** Further research is required to formulate standardized designs and construction techniques for masonry stone arch bridge structures
- **Training Programs**: training programs should be established to build capacity of local contractors and engineers in the construction and maintenance of masonry stone arch bridges
- **Adoption in Rural Infrastructure Development:** masonry Stone arch bridges could be adopted in future rural infrastructure development projects in Uganda in relation to short spans
- **Curriculum and Professional Training**: Some modules on alternate bridge technology, such as stone arched structures, should be included in the curriculum for civil engineers in technical institutes and universities. Continuing professional development courses for engineers should stress design, construction and maintenance knowledge.
- **Establishment of Lifecycle Benchmarks:** The development of national-level benchmarks for lifecycle costs, embodied energy and resilience can aid in making informed investment choices for bridge infrastructures.
- **Decentralized Procurement and Local Capacity Development:** Empower district engineers and local governments to procure and implement masonry bridge projects by standardizing Bill of Quantities (BoQs), offering training for local masons, and enabling community-based monitoring and maintenance systems.
- **Strategic Research and Development (R&D):** Additional research studies on the durability of local stones, mortar mix designs, and arch designs in varying hydrological and geotechnical settings in Uganda’s ecological regions should also be supported.
- **Integration with Digital Technologies:** Advocate for integration with building information modeling technology in simulating modular units in stone arch bridge construction for the creation of templates for contractors and local governments to adapt to.
- **Pilot Projects/Demonstration Projects:** Establish pilot projects with local governments to demonstrate the efficacy of re-engineered stone arch bridge technology. Record experiences for future replication on a larger scale.

5. Acknowledgement

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