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# Cost and Load Effect Comparisons Between Reinforced Concrete Integral and Non-Integral Bridge Using Experimental and Analytical Examinations

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**Abstract**

*Bridges without joints or bearings are referred to as "integral bridges," while bridges with joints and expansion joints are referred to as "non integral bridges. This study aims to examine the cost differences between the integral and non-integral bridge of the same length and height using analytical and experimental investigations. Modelling, analysis, design, detailing and costing of 15m,20m, 22.5m and 25m single span reinforced concrete girder integral bridge and 15m,20m, 22.5m and 25m single span reinforced concrete girder non integral bridge were done. The experimental program included six reinforced concrete bridge models three integral bridge models; namely, a) 1000mm length, 600mm high and 95mm thick b)1250mm length,600mm high and 105mm thick c) 1500mm length,600mm high and 120mm thick and three additional non-integral bridge model of the same sizes and reinforcements. Analytical examinations were made for six integral bridges and six non-integral bridges for verifications. The experimental results reveals that the MIDS CIVIL finite element software is in agreement with the results obtained within +/- 10% and recommended to be used in the design. The priced bill of quantities based on the design reveals that the decrease of cost by 19.1% to 20.0% for integral bridge as compared to non-integral bridges with the same length and height. It is recommended that planners and engineers embrace integral design and construction by reviewing the road design handbook, which specifies that integral design must take precedence over non-integral concepts to save costs.*

**Keywords:** Cracking loads, integral bridge models, non-integral bridge models, ultimate failure loads

## INTRODUCTION

It can be seen that the proportion of bridges that are 'integral' has increased significantly in this Period and now accounts for about half of the total bridge construction in UK. (Peter, et.al, 2006).

The study's goals are to model, analyze, design, and estimate the cost of integral and non-integral through experimental and analytical examinations; and, in the end, assess whether the results of the analyses and experiments agree.

Integral bridge construction and design are appropriate for tropical climates with moderate temperature variations.

## THEORY

This study involves literature research, experimental research and finite element based structural modelling, analysis and design. **Figures 1a&b** shows that non-integral bridges deteriorated due to leakage of water through the expansion joints and bridge seats that eventually lead to corrosion. (Martin.et.al, 2009).

It can be seen that the proportion of bridges that are 'integral' has increased significantly in this Period and now accounts for about half of the total bridge construction in UK. (Peter, et.al, 2006).

### Horizontal earth pressure on the integral abutments

Abutment of the integral bridge experiences cyclic loadings due to expansion and contraction of the deck due to daily and annual temperature variations. Due to this, there exists complicated soil

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structure interactions that creates uncertainties in the design of integral bridges. Avoiding the joints and bearings have significantly reduce the overall cost and maintenance of the structure and it is becoming increasingly popular in many countries (Alan G.et al, 2012). Lateral earth pressure can be as high as the maximum passive earth pressures or as low as the minimum active earth pressure based on the horizontal displacement of the abutments due to temperature variations (Sami A, et al, 1999).

The horizontal earth pressure on the abutment wall of integral bridges is cyclical; it increases when the bridge expands and decreases when the bridge contracts. **Fig 1a&b to Fig 5** show how the lateral horizontal earth pressure on the abutments vary during expansion and contraction.

The additional stress induced in the frame type of the integral bridges due to thermal expansion of the deck are controlled to large extent by the backfill soil adjacent to the abutments (B.M.Lehane et.al 1999).

**Study Hypothesis**

The following are study hypothesis:

1. Integral bridges perform better than non-integral bridges and are cost effective.

**FIGURE 1 (a)**
Damage due to corrosion for non-integral bridges
**Source:** Martin.et.al, (2009)

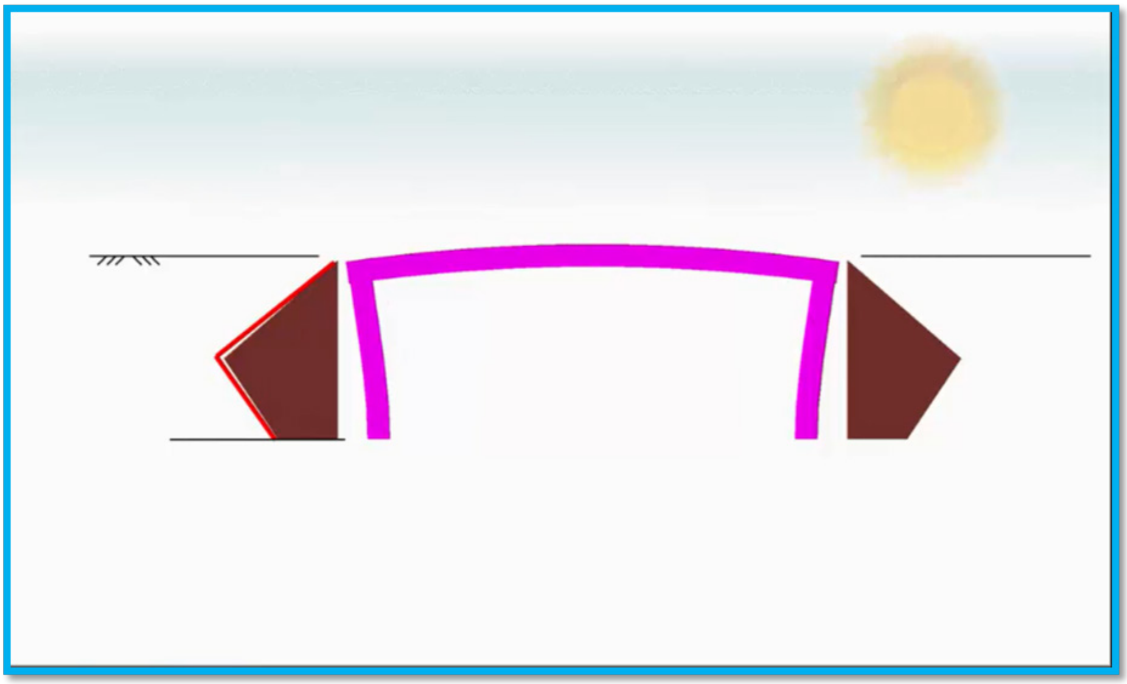

**FIGURE 1 (b)**
Lateral earth pressure on abutments during bridge expansion
**Source:** Alan G.et al, (2012)

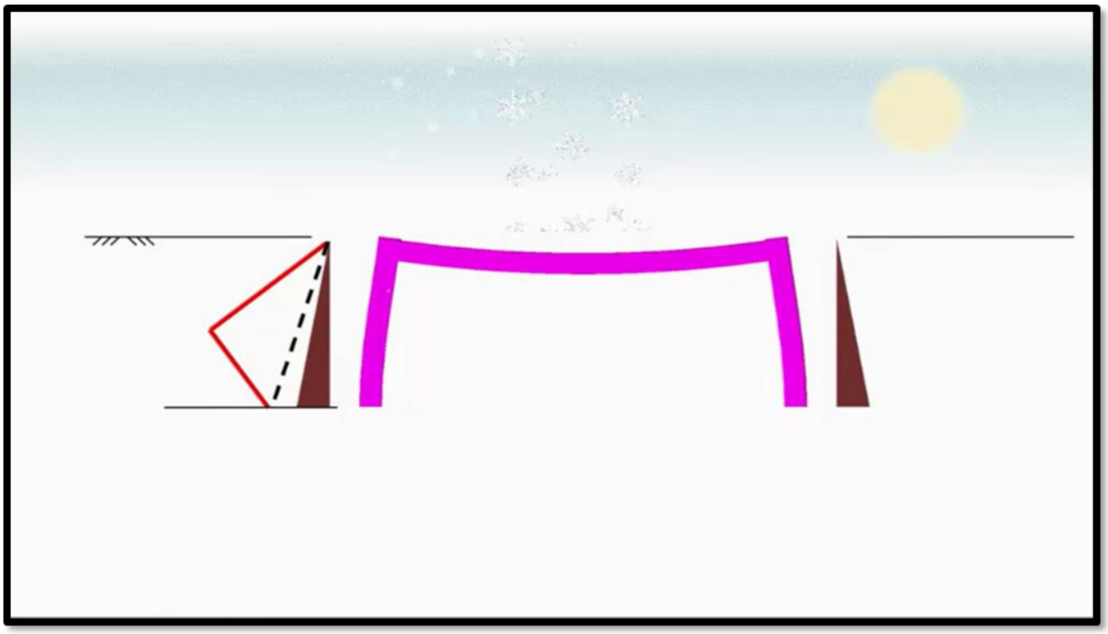

**FIGURE 2**
Lateral earth pressure on abutments during bridge contraction
**Source:** Alan G.et al, (2012)

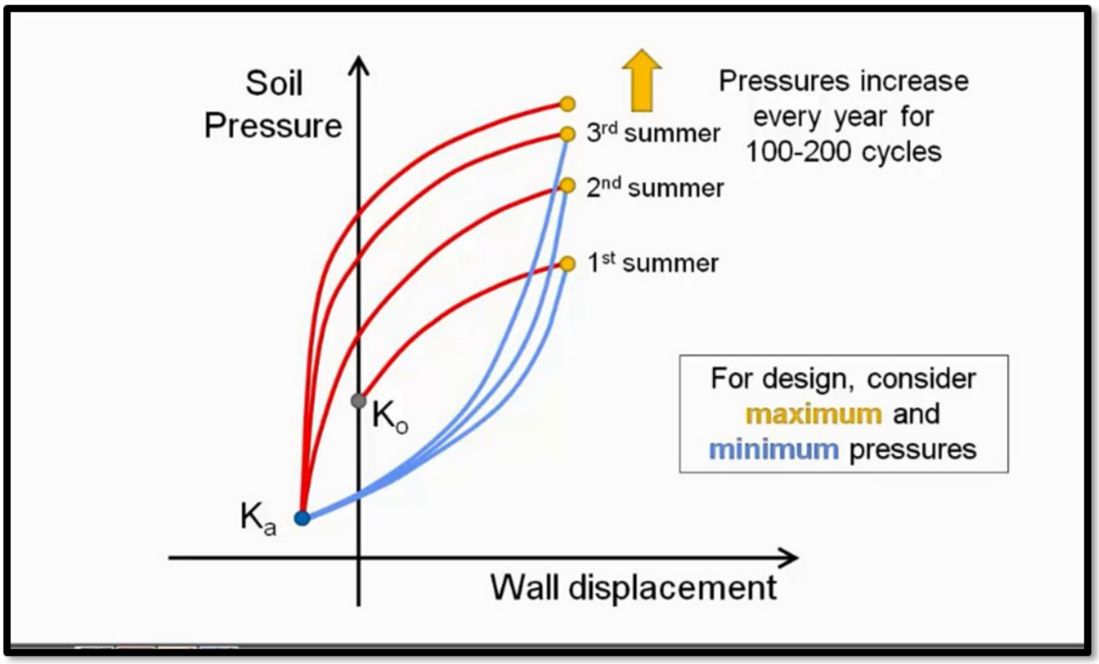


**FIGURE 3**
Cyclic lateral earth pressure during bridge expansion and contraction
**Source:** Alan G.et al, (2012)

2. Maximum deflection of integral bridge is less than non-integral bridge of the same size.
3. The ultimate load capacity of the integral bridge is higher than non-integral bridge at failure.

**Experimental Program**

The experimental program in this paper consists of two phases. The first phase was to prepare the six bridge models as per the structural drawings prepared and cast following all the procedures and specifications required. The second phase aimed at loading the bridge models till ultimate failure and analysis of the results obtained from

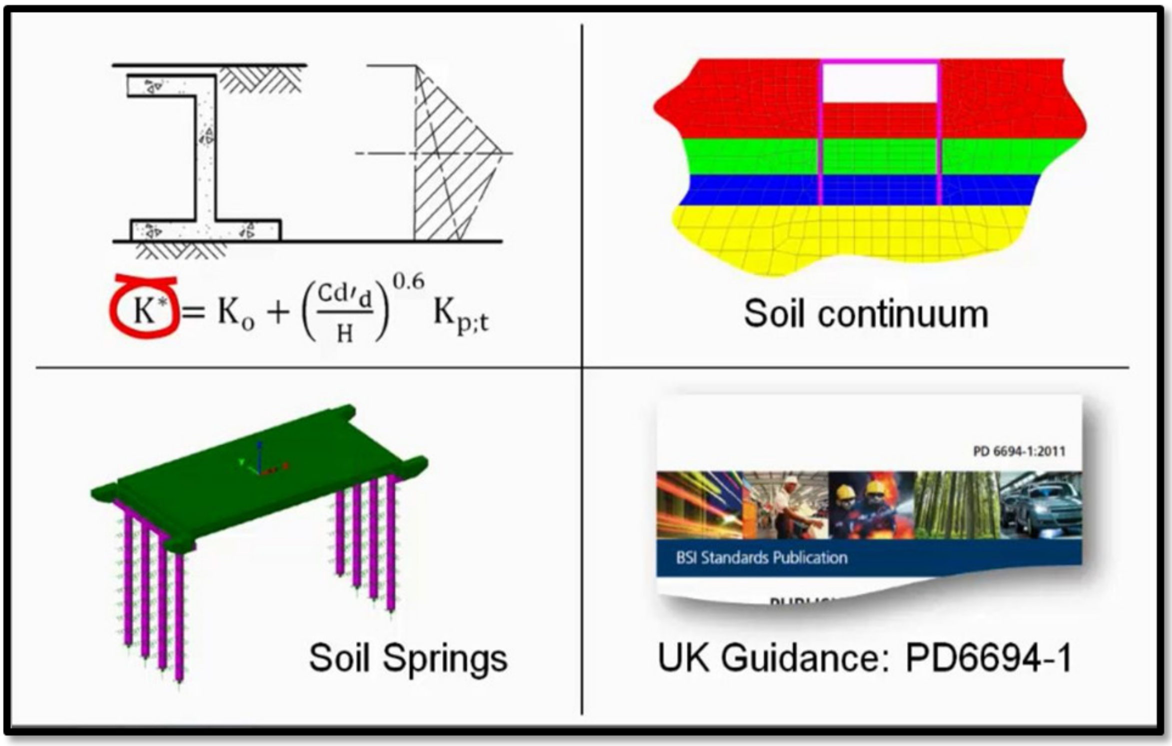


**FIGURE 4**
Different types of soil model in the integral bridge contraction
**Source:** Alan G.et al, (2012)

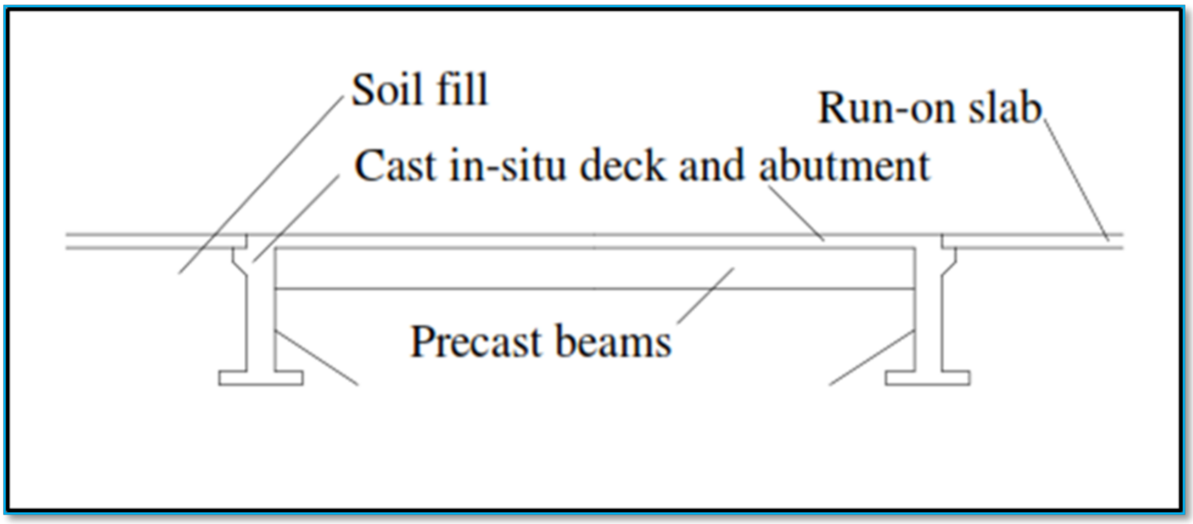


**FIGURE 5**
Framed integral bridge
**Source:** Lehane B.M. et.al, (1999)

the loading tests.

**Description of the Models and Details**

The models are three integral bridge models. **Figure 6(b) to Figure 6(c)** illustrate geometry and reinforcement details of the bridge model samples while **Figure 6(a)** illustrates the schematic drawings of integral and non-integral bridge models. **Table 1** shows the properties of the bridge models and materials used, while **Table 2** show the main longitudinal steel reinforcements used and properties.

**Materials Used**

**Concrete**

**Table 3, Table 4** and **Table 5** show some of the

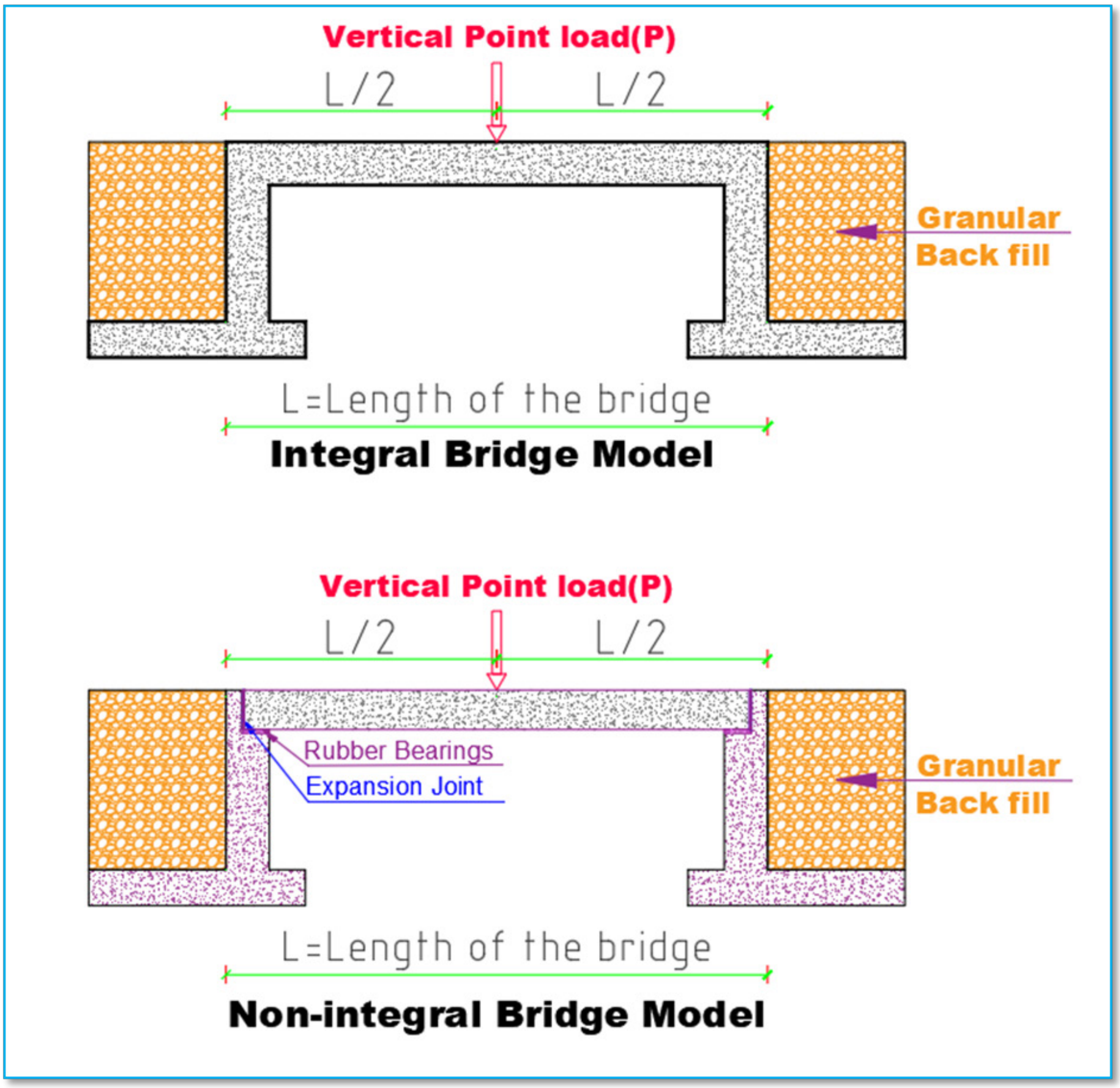


**FIGURE 6(a)**
Integral and non-integral bridge models loading schematic drawing
**Source:** Author, 2024

**TABLE 1**
Properties of the bridge models deck slab and materials used

| Bridge Model | Model Type | Slab Thick. [mm] | Slab width [mm] | Length of the bridge model [mm] | Compressive Strength (28 Days Cylindrical) $f_{ck}$[MPa] | Steel Yield Strength $f_{yk}$[MPa] | Modulus of Elasticity Concrete Ec[MPa]] |
|---|---|---|---|---|---|---|---|
| 1 | Integral | 95 | 500 | 1000 | 35 | 420 | 32,837 |
| 2 | Non-integral | 95 | 500 | 1000 | 35 | 420 | 32,837 |
| 3 | Integral | 105 | 500 | 1250 | 35 | 420 | 32,837 |
| 4 | Non-integral | 105 | 500 | 1250 | 35 | 420 | 32,837 |
| 5 | Integral | 120 | 500 | 1500 | 35 | 420 | 32,837 |
| 6 | Non-integral | 120 | 500 | 1500 | 35 | 420 | 32,837 |

**Source:** Author, 2024

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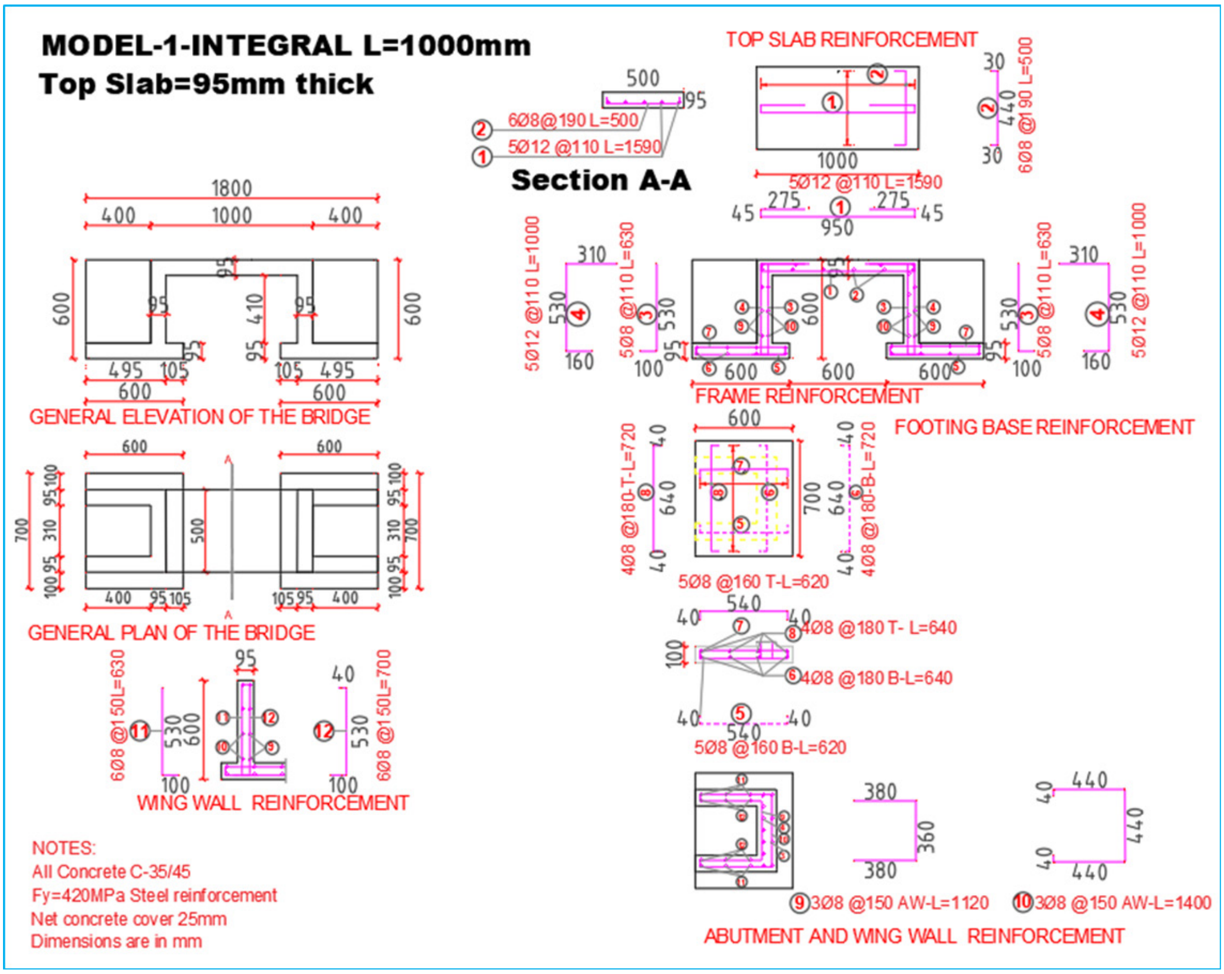


**FIGURE 6(b)**
Geometrical and structural drawings of the Integral bridge model-1 Length=1000mm
**Source:** Author, 2024

**TABLE 2**
Properties of the bridge models deck slab and materials used

| Bridge Model | Model Type | Length of the bridge model [mm] | Area of tension reinforcement used [mm2] | Steel Yield Strength $f_y$[MPa] | Ultimate Steel Tensile Strength fu[MPa] | Modulus of Elastiity Steel [GPa] |
|---|---|---|---|---|---|---|
| 1 | Integral | 1000 | 566 | 420 | 500 | 200 |
| 2 | Non-integral | 1000 | 566 | 420 | 500 | 200 |
| 3 | Integral | 1250 | 679 | 420 | 500 | 200 |
| 4 | Non-integral | 1250 | 679 | 420 | 500 | 200 |
| 5 | Integral | 1000 | 792 | 420 | 500 | 200 |
| 6 | Non-integral | 1000 | 792 | 420 | 500 | 200 |

**Source:** Author, 2024

basic properties of the materials used in the concrete mix design and the result obtained. **Figure 7** shows the particle size distributions of the aggregates mix used in the concrete mix.

The production of cement is very costly and it is one of the major human activities responsible in the rise of Co2 –emissions. To minimize the cost of concrete production and reduce the negative

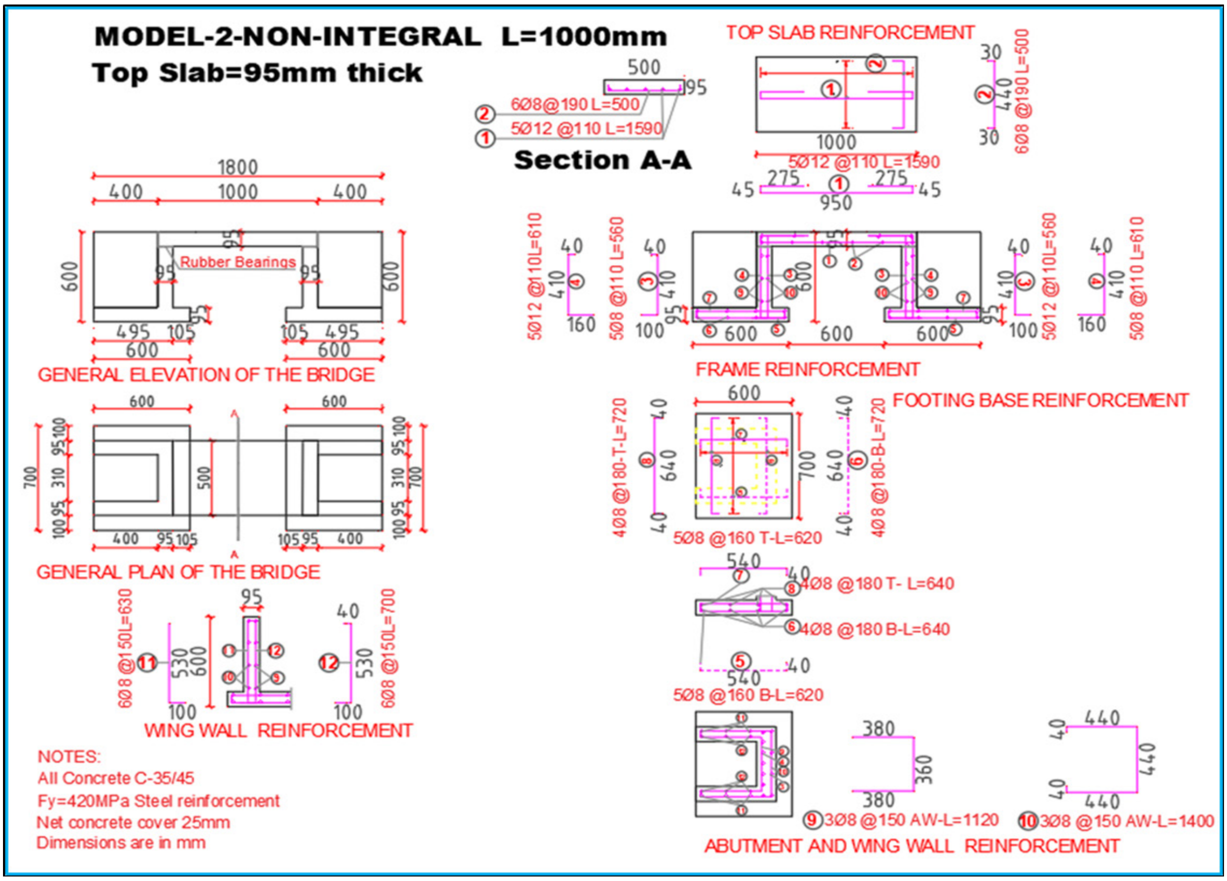


**FIGURE 6(c)**
Geometrical and structural drawings of the Non-integral bridge model-2 Length=1000mm
**Source:** Author, 2024

**TABLE 3**
Material properties of materials used in the mix design

| I. No | Material Description | Loose Density [Kg/m3] | Dry Rodded Density [Kg/m3] | Bulk Specific Gravity SSD | Absorption [%] | Moisture Content [%] |
|---|---|---|---|---|---|---|
| 1 | Cement 42.5N | 1440.00 | Not Required | 3.15 | Not Required | Not Required |
| 2 | Aggregate 0/6mm | 1331.06 | 1482.25 | 2.45 | 3.50 | 6.5 |
| 3 | Aggregate 6/10mm | 1303.40 | 1372.00 | 2.45 | 2.10 | 1.0 |
| 4 | Aggregate 10/20mm | 1317.18 | 1408.75 | 2.45 | 1.80 | 1.0 |
| 5 | Combined Coarse aggregate | 1421.05 | 1597.40 | 2.45 | 1.95 | |

**Source:** Author, 2024

environmental impact due to Co2 emissions, it is important to use innovative technology and method for the design of concrete structures and concrete mixes (Mellese Yimam, et.al, 2023). The particle packing technology is used in the concrete mix design.

**TABLE 4**
Material used in the mix design-1m³

| I.No. | Eurocode Designation | Characteristics Cylinder Strength | Characteristics Cube Strength | Water SSD | Cement 42.5 N | Admixture DYNAMON | Aggregate 0mm/6mm | Aggregate 6mm/10mm | Aggregate 10mm/20mm | Estimated Density (2% Air) | Water +Admixture) to Cement ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Class | MPa | MPa | Lt/m³ | Kg/m³ | Lt/m³ | Kg/m³ | Kg/m³ | Kg/m³ | Lt/m³ | Ratio |
| 1 | C35/45 | 35.0 | 45.0 | 139.0 | 358.9 | 4.6 | 842.1 | 324.8 | 603.3 | 2273.1 | 0.40 |

**Source:** Author, 2024

**TABLE 5**
Average compressive strengths at 3days, 7days and 28days, slump and density of Concrete mix obtained at laboratory

| I.No. | Eurocode Designation | Average Observed Slump | 3 Days Cubic Strength | 7 Days Cubic Strength | 28 Days Cubic Strength | Density of the Concrete | Admixture Used | Aggregate Concrete Ratio | Water +Admixture) to Cement ratio |
|---|---|---|---|---|---|---|---|---|---|
| | Class | mm | MPa | MPa | MPa | Kg/m³ | Lt/m³ | Kg/Kg | Ratio |
| 1 | C35/45 | 100/180 | 32.1 | 42.1 | 57.0 | 2275 | 4.6 | 0.78 | 0.40 |

**Source:** Author, 2024

## RESULTS AND DISCUSSION

### Bridges Models General Behaviour

The load was applied using a hydraulic Jack with increment of 10kN ever 1mininute until failure. **Figure 8** and **Figure 9** show the shape and the mechanism of the failed bridge models. Initially no cracks were observed and showed elastic behavior. After increasing the applied load, vertically oriented flexural cracks appeared at the middle of the bridge models for non-integral bridge models that showed ductile failure. With further increasing the applied load the flexural-shear cracks propagated towards the supports. The mode of failures for non-integral bridge models were flexural tension cracks associated with the yielding of the steel and tensile failure of the concrete while in the integral bridge models shear-flexural fails occurred at the support and mid spans.

### Ultimate Failure Loads Capacity

The computations show that minimum ultimate failure loads were obtained for flexural in the non-integral bridge and minimum ultimate failure loads were obtained for shear for in the integral bridges. **Table 6** presents the analytical computation of ultimate flexural failure loads capacity for bridges and **Table 7** presents the analytical computations of ultimate shear failure loads without transverse shear reinforcements. **Table 8** presents the ultimate final failure loads computed and the expected mode of failure. Computation results show that integral bridges fails in shear and non-integral bridges fail in flexural tension. **Table 9** shows the ratio of the ultimate failure loads of integral to non-integral bridges obtained from analytical computations. **Table 10** summarizes the experimentally measured ultimate failure loads and observed mode of failure for the six bridge models. **Table 11** shows the ratio of the ultimate

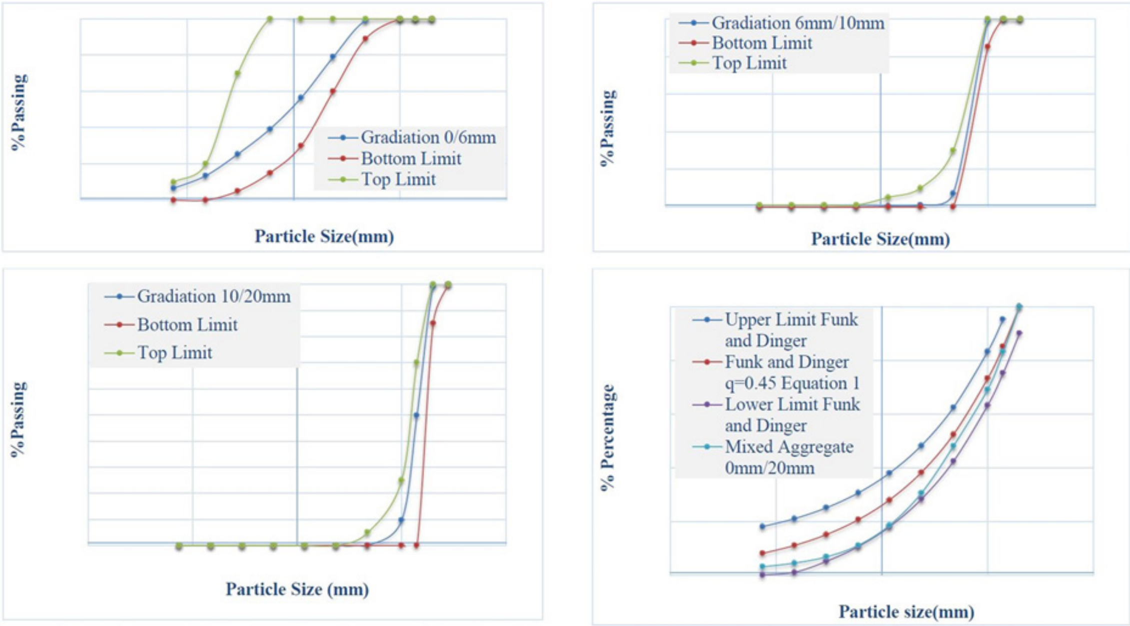


**FIGURE 7**
Mixed aggregate 0/20mm gradation for concrete C35/40 mix
**Source:** Author, 2024

**FIGURE 8**
Failed Non-integral bridge model
**Source:** Author, 2024

failure loads of integral to non-integral bridges obtained from experimental computations. **Figure 10 to Figure 17** show the ultimate failure loads experimentally obtained and analytically computed; and the comparisons among them.

**FIGURE 9**
Failed integral bridge model
**Source:** Author, 2024

**TABLE 6**
Computed ultimate flexural failure loads

| | | | |
|---|---|---|---|
| Compressive Strength (28 Days Cylindrical) | $f_{ck}$[MPa] | 35 | $Icracking = \left(\frac{1}{3}\right)bc^3 + nAs(d-c)^2$ |
| Compressive Strength (28 Days Cubic) | $f_{ck,cube}$[MPa] | 45 | |
| Yield Strength of the steel | $f_{yk}$[MPa] | 420 | $Myeild = \frac{Icr\ Fy}{n(d-c)}$ |
| Secant Modulus of Elasticity of concrete | Ecm[MPa] | 34,07 | |
| Modulus of Elasticity of steel | Est[MPa] | 200,0 | $Mcrushing = 0.30Fckbd2$ |
| Modular Ratio of Est/Econ | n | 5.9 | $C = \frac{-nAs + \sqrt{(nAs)^2 + 2nAsbd}}{b}$ |
| Ultimate Failure load/Yield failure loads Estimated | Ratio | 1.20 | |

| Br. Model | Model Type | Length of the model [mm] | Slab thick [mm] | Eff. Dep. [mm] | L/d | Area of steel [mm2] | Reinf Ratio ρ[%] | Comp depth C [mm] | Slab width [mm] | Cracked moment of inertia Icr-mm4 x1000,000 | Crushing Flexural moment Capacity Mcr. [kNm] | My Yield moment [kNm] | Vertical Flexural Yield Load Pu;yd [kN] | Vertical Ultimate Flexural Failure Load Pu,fl [kN] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Integral | 1,000 | 95 | 64 | 15.6 | 565 | 1.8 | 23 | 500 | 7.6 | 21.5 | 13.4 | 116 | 140 |
| 2 | Non-integral | 1,000 | 95 | 64 | 15.6 | 565 | 1.8 | 23 | 500 | 7.6 | 21.5 | 13.4 | 63 | 75 |
| 3 | Integral | 1,250 | 105 | 74 | 16.9 | 679 | 1.8 | 27 | 500 | 12.1 | 28.7 | 18.5 | 121 | 146 |
| 4 | Non-integral | 1,250 | 105 | 74 | 16.9 | 679 | 1.8 | 27 | 500 | 12.1 | 28.7 | 18.5 | 70 | 84 |
| 5 | Integral | 1,500 | 120 | 89 | 16.9 | 792 | 1.8 | 32 | 500 | 20.6 | 41.6 | 26.0 | 135 | 162 |
| 6 | Non-integral | 1,500 | 120 | 89 | 16.9 | 792 | 1.8 | 32 | 500 | 20.6 | 41.6 | 26.0 | 84 | 100 |
| 7 | Integral- Ref.1 | 2,000 | 150 | 117 | 17.1 | 1,206 | 1.7 | 42 | 600 | 54.6 | 86.2 | 52.2 | 207 | 248 |
| 8 | Non-integral- | 2,000 | 150 | 117 | 17.1 | 1,206 | 1.7 | 42 | 600 | 54.6 | 86.2 | 52.2 | 126 | 152 |
| 9 | Integral- Ref.2 | 2,500 | 175 | 142 | 17.6 | 1,810 | 1.7 | 51 | 750 | 121.1 | 158.8 | 95.0 | 338 | 406 |
| 10 | Non-integral- | 2,500 | 175 | 142 | 17.6 | 1,810 | 1.7 | 51 | 750 | 121.1 | 158.8 | 95.0 | 185 | 222 |
| 11 | Integral- Ref.3 | 3,000 | 200 | 167 | 18.0 | 2,815 | 1.7 | 60 | 1000 | 261.1 | 292.8 | 174.0 | 457 | 549 |
| 12 | Non-integral- | 3,000 | 200 | 167 | 18.0 | 2,815 | 1.7 | 60 | 1000 | 261.1 | 292.8 | 174.0 | 281 | 337 |

**Source:** Author, 2024

**TABLE 7**

Computed ultimate shear failure loads without shear reinforcement as per the Euro code

| | | |
|---|---|---|
| Compressive Strength (28 Days Cylindrical) | $f_{ck}$[MPa] | 35 |
| Compressive Strength (28 Days Cubic) | $f_{ck,cube}$[MPa] | 45 |
| Yield Strength of the steel | $f_{yk}$[MPa] | 420 |
| $C_{RD,c}$ | Ratio | 0.12 |
| υ=0.6(1-fck/250) | Ratio | 0.516 |
| Failure Shear strength/Design shear strength | Ratio | 1.50 |

$$V_{RD\ 21.8} = 0.124 \upsilon f ck b d$$

$$Vd = C_{RD} K (100 \rho f ck)^{1/3} bd$$

| Bridge Model | Model Type | Length of the model [mm] | Slab thick. [mm] | Effective Depth [mm] | L/d | Area of steel [mm2] | Reinf. Ratio ρ[%] | Depth factor K | Maximum Shear Limit VRD,21.8 [kN] | Failure Shear Strength Vd[kN] | Vertical Ultimate Shear Failure Load Pu; shear [kN] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Integral | 1,000 | 95 | 64 | 15.6 | 565 | 1.8 | 2.0 | 69.4 | 45.6 | 89.9 |
| 2 | Non-integral | 1,000 | 95 | 64 | 15.6 | 565 | 1.8 | 2.0 | 69.4 | 45.6 | 89.9 |
| 3 | Integral | 1,250 | 105 | 74 | 16.9 | 679 | 1.8 | 2.0 | 80.2 | 53.3 | 105.0 |
| 4 | Non-integral | 1,250 | 105 | 74 | 16.9 | 679 | 1.8 | 2.0 | 80.2 | 53.3 | 105.0 |
| 5 | Integral | 1,500 | 120 | 89 | 16.9 | 792 | 1.8 | 2.0 | 96.4 | 63.5 | 124.7 |
| 6 | Non-integral | 1,500 | 120 | 89 | 16.9 | 792 | 1.8 | 2.0 | 96.4 | 63.5 | 124.7 |
| 7 | Integral- Ref.1 | 2,000 | 150 | 117 | 17.1 | 1,206 | 1.7 | 2.0 | 152.0 | 99.0 | 194.0 |
| 8 | Non-integral- | 2,000 | 150 | 117 | 17.1 | 1,206 | 1.7 | 2.0 | 152.1 | 99.0 | 193.5 |
| 9 | Integral- Ref.2 | 2,500 | 175 | 142 | 17.6 | 1,810 | 1.7 | 2.0 | 230.8 | 149.7 | 291.1 |
| 10 | Non-integral- | 2,500 | 175 | 142 | 17.6 | 1,810 | 1.7 | 2.0 | 230.8 | 149.7 | 291.1 |
| 11 | Integral- Ref.3 | 3,000 | 200 | 167 | 18.0 | 2,815 | 1.7 | 2.0 | 361.9 | 234.0 | 453.1 |
| 12 | Non-integral- | 3,000 | 200 | 167 | 18.0 | 2,815 | 1.7 | 2.0 | 361.9 | 234.0 | 453.1 |

**Source:** Author, 2024

**TABLE 8**

Summary of the computed failure loads and expected mode of failure

| Bridge Model | Model Type | Length of the model [mm] | Slab thick. [mm] | Vertical Ultimate flexural Failure Load Pu,fl [kN] | Vertical Ultimate Shear Failure Load Pu; shear[kN] | Final Failure Load-Pu Min [Shear, flexure [kN] | Mode of failure expected |
|---|---|---|---|---|---|---|---|
| 1 | Integral | 1,000 | 95 | 140 | 89.9 | 89.9 | Shear |
| 2 | Non-integral | 1,000 | 95 | 75.3 | 89.9 | 75.3 | Flexure |
| 3 | Integral | 1,250 | 105 | 146 | 105.0 | 105.0 | Shear |
| 4 | Non-integral | 1,250 | 105 | 84.1 | 105.0 | 84.1 | Flexure |
| 5 | Integral | 1,500 | 120 | 162 | 124.7 | 124.7 | Shear |
| 6 | Non-integral | 1,500 | 120 | 100.3 | 124.7 | 100.3 | Flexure |
| 7 | Integral- Ref.1 | 2,000 | 150 | 248 | 194.0 | 194 | Shear |
| 8 | Non-integral Ref.1 | 2,000 | 150 | 151.8 | 193.5 | 151.8 | Flexure |
| 9 | Integral- Ref.2 | 2,500 | 175 | 406 | 291.1 | 291.1 | Shear |
| 10 | Non-integral Ref.2 | 2,500 | 175 | 222.2 | 291.1 | 222.2 | Flexure |
| 11 | Integral- Ref.3 | 3,000 | 200 | 549 | 453.1 | 453.1 | Shear |
| 12 | Non-integral Ref.3 | 3,000 | 200 | 337.1 | 453.1 | 337.1 | Flexure |

**Source:** Author, 2024

**TABLE 9**
Computed ratio of integral to non-integral ultimate failure loads

| Bridge Model | Length of the model [mm] | Slab thick. [mm] | Final Failure Load of Integral bridge [Shear, flexure] [kN] | Final Failure Load of Non-integral bridge [Shear, flexure] [kN] | Percentage increase of failure load from non-integral to integral [%] | Ratio of Failure loads Integral/Non-integral |
|---|---|---|---|---|---|---|
| 1 | 1,000 | 95 | 89.9 | 75.3 | 19.4% | 1.19 |
| 2 | 1,250 | 105 | 105.0 | 84.1 | 24.9% | 1.25 |
| 3 | 1,500 | 120 | 124.7 | 100.3 | 24.3% | 1.24 |
| 4 | 2,000 | 150 | 193.5 | 151.8 | 27.5% | 1.28 |
| 5 | 2,500 | 175 | 291.1 | 222.2 | 31.0% | 1.31 |
| 6 | 3,000 | 200 | 453.1 | 337.1 | 34.4% | 1.34 |

**Source:** Author, 2024

**TABLE 10**
Summary of the experimentally measured ultimate failure loads and observed mode of failure

| Bridge Model | Model Type | Length of the model [mm] | Slab thick. [mm] | Final Failure Load-Pu Min [Shear, flexure [kN] | Mode of failure observed |
|---|---|---|---|---|---|
| 1 | Integral | 1,000 | 95 | 98.9 | Shear |
| 2 | Non-integral | 1,000 | 95 | 81.0 | Flexure |
| 3 | Integral | 1,250 | 105 | 117.6 | Shear |
| 4 | Non-integral | 1,250 | 105 | 89.2 | Flexure |
| 5 | Integral | 1,500 | 120 | 135.6 | Shear |
| 6 | Non-integral | 1,500 | 120 | 109.0 | Flexure |

**Source:** Author, 2024

**TABLE 11**
Experimentally measured ratio of integral to non-integral ultimate failure loads

| Bridge Model | Length of the model [mm] | Slab thick. [mm] | Final Failure Load of Integral bridge [Shear, flexure] [kN] | Final Failure Load of Non-integral bridge [Shear, flexure] [kN] | Percentage increase of failure load from non-integral to integral [%] | Ratio of Failure loads Integral/ Non-integral |
|---|---|---|---|---|---|---|
| 1 | 1,000 | 95 | 98.9 | 81.0 | 22.1% | 1.22 |
| 2 | 1,250 | 105 | 117.6 | 89.2 | 31.9% | 1.32 |
| 3 | 1,500 | 120 | 135.6 | 109.0 | 24.3% | 2.17 |

**Source:** Author, 2024

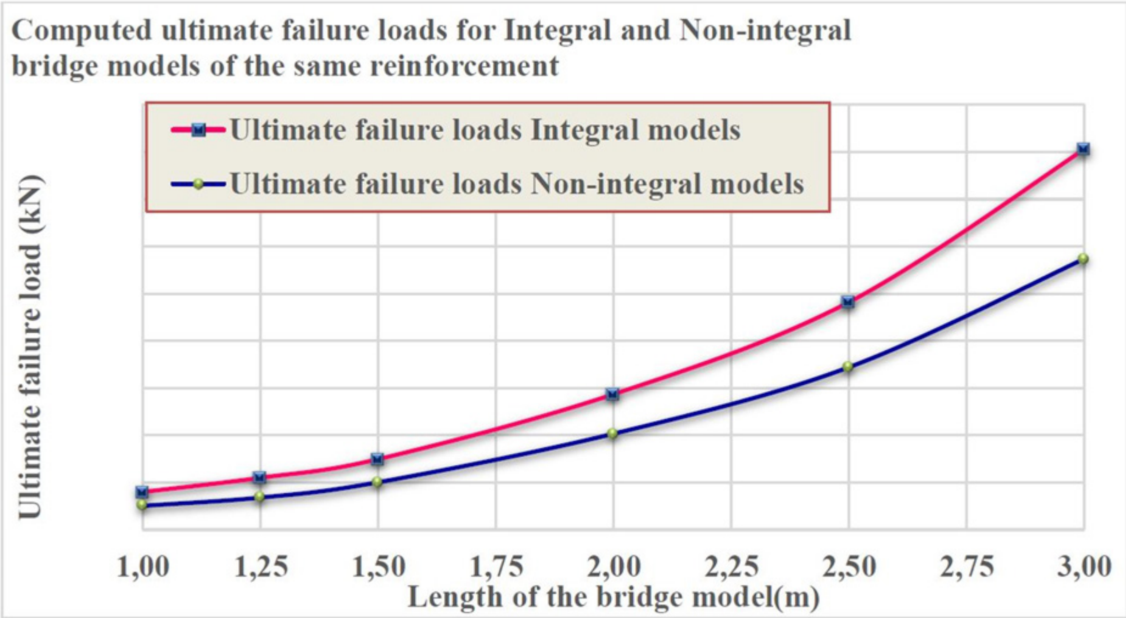


**FIGURE 10**
Computed ultimate vertical failure loads for integral and non-integral bridges
**Source:** Author, 2024

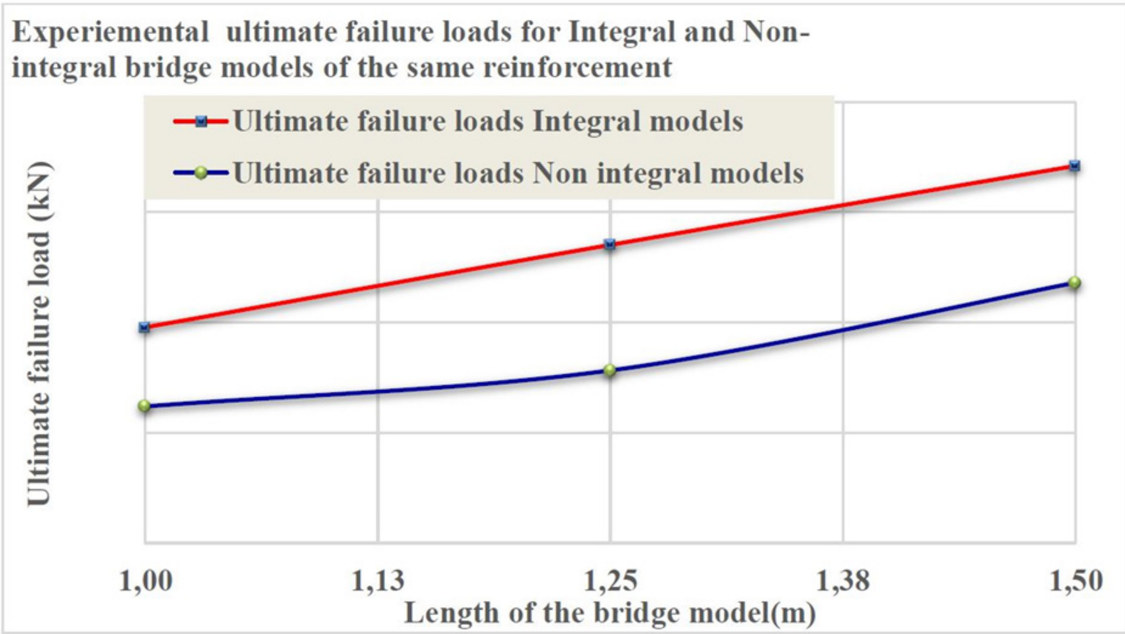


**FIGURE 11**
Experimental ultimate vertical failure loads for integral and non-integral bridges
**Source:** Author, 2024

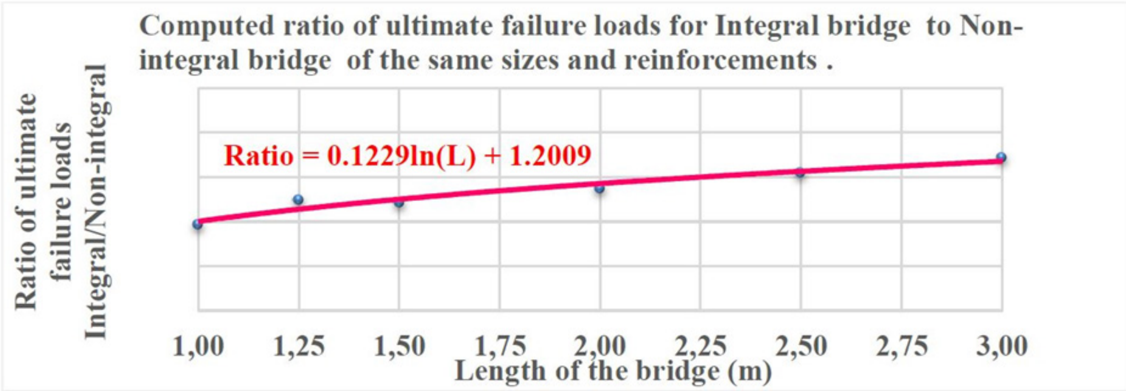


**FIGURE 12**
Computed ratio of ultimate failure loads for integral and non-integral bridges of the same sizes and reinforcement
**Source:** Author, 2024

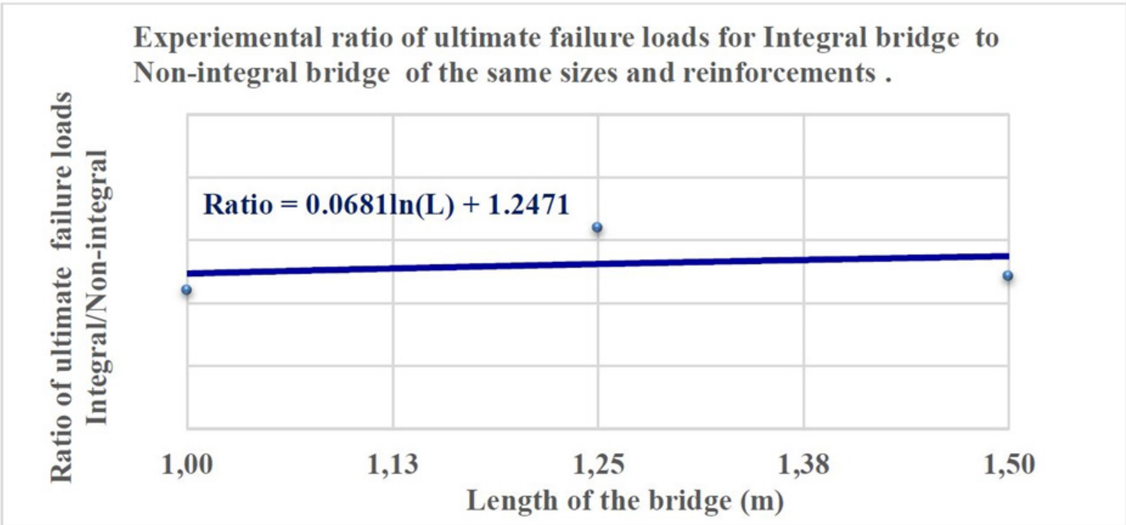


**FIGURE 13**
Experimentally obtained ratio of ultimate failure loads for integral and non-integral bridges of the same sizes and reinforcement
**Source:** Author, 2024

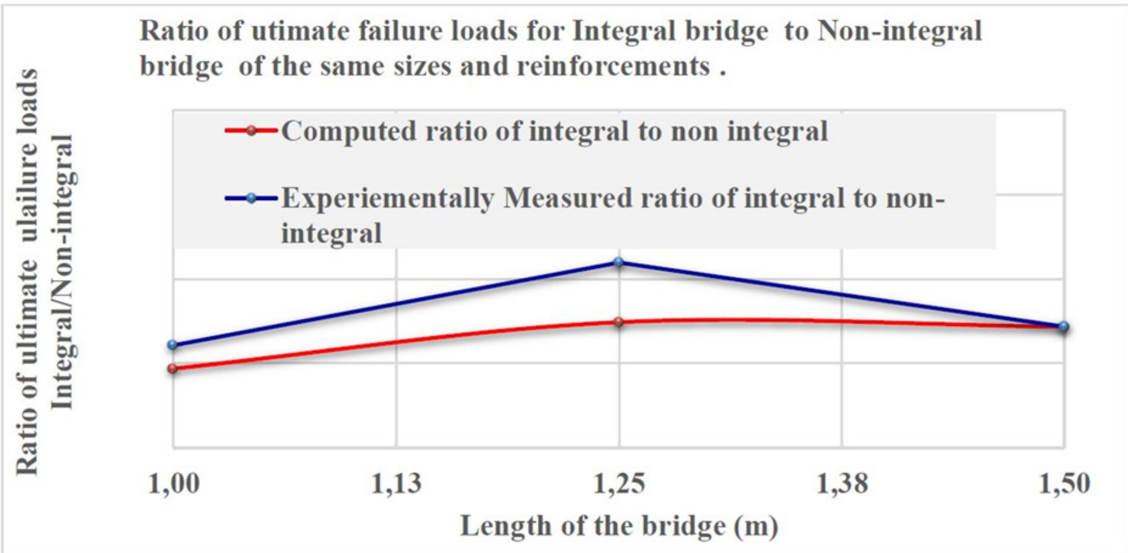


**FIGURE 14**
Experimentally obtained and computed ratio of ultimate failure loads for integral and non-integral bridges of the same sizes and reinforcement
**Source:** Author, 2024

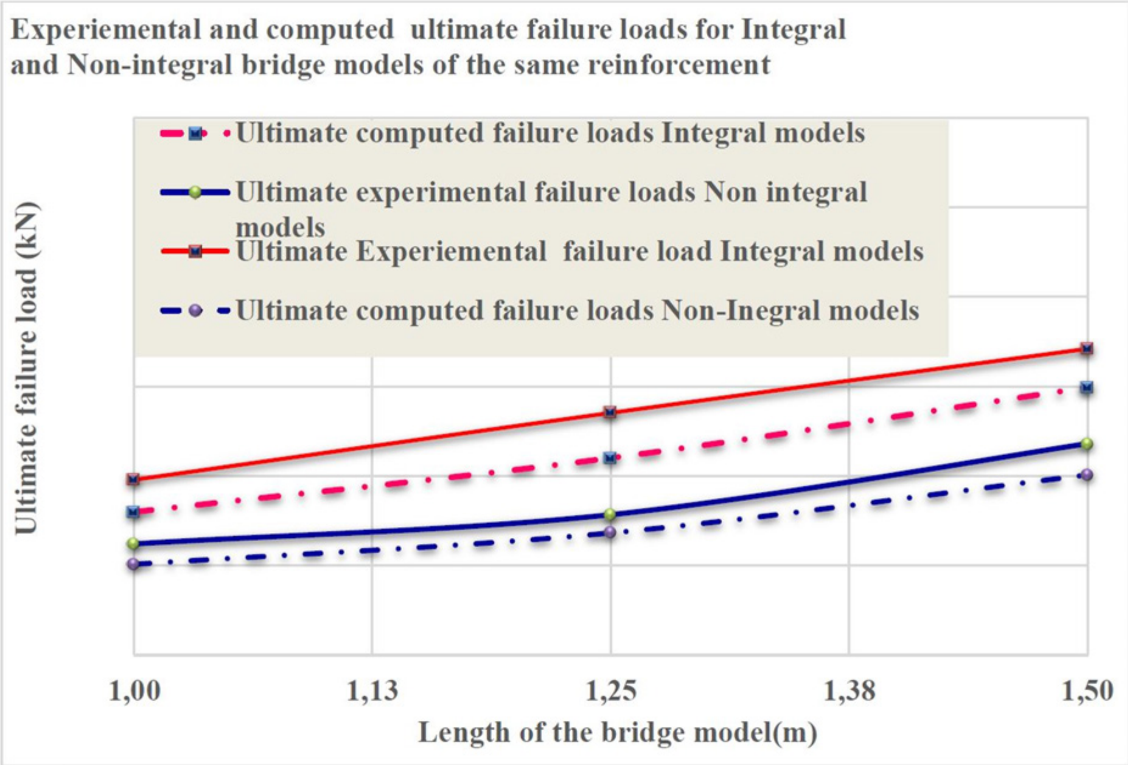


**FIGURE 15**
Computed and measured ultimate failure loads Integral to Non-integral Bridge models
**Source:** Author, 2024

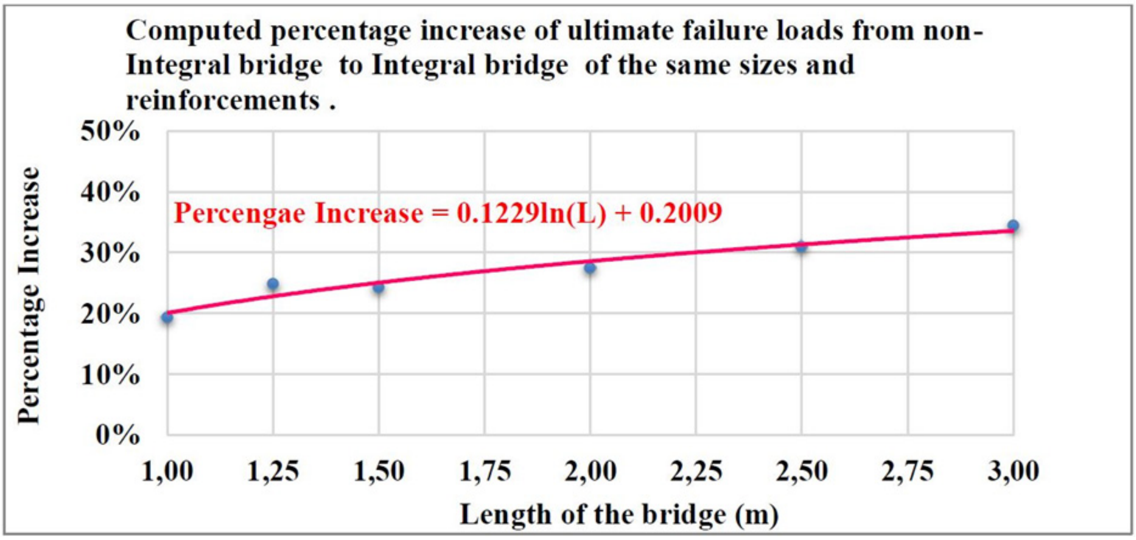


**FIGURE 16**
Computed percentage increase of ultimate failure loads for integral and non-integral bridges of the same sizes and reinforcement
**Source:** Author, 2024

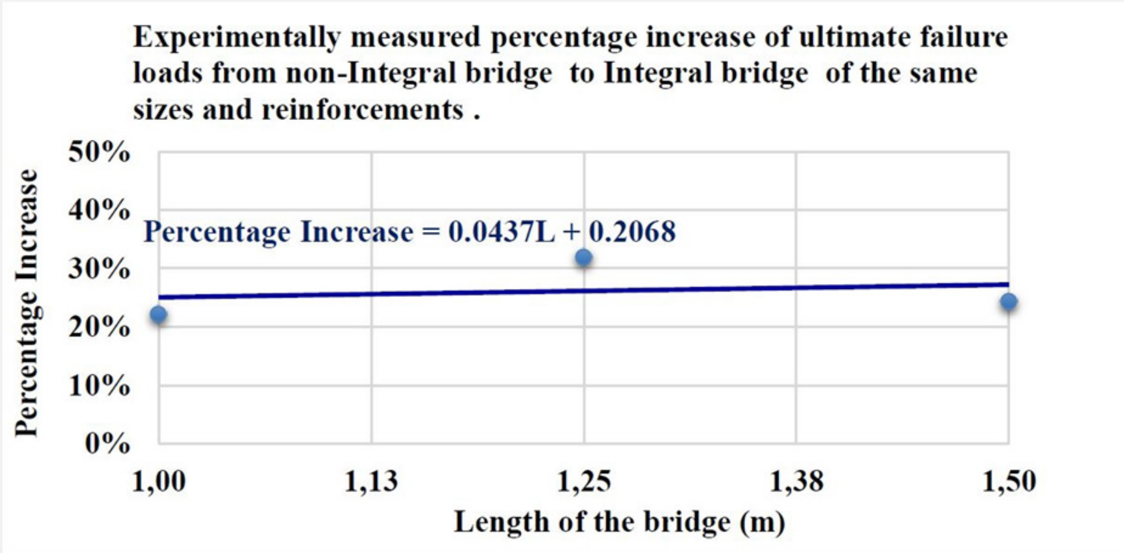


**FIGURE 17**
Experimentally measured percentage increase of ultimate failure loads for integral and non-integral bridges of the same sizes and reinforcement
**Source:** Author, 2024

The experimental results obtained in regards to ultimate failure loads show that it is in consistence with the theories that integral construction carries more load and deflect less.

**Midas Civil Analytical Computations**
Analytical analyses were done using MIDAS CIVIL finite element analysis software as presented in **Tables 12 to 20**.

**TABLE 12**
Properties of materials and loading data used in the modelling, analysis and design of the models

| I.No | Material Type | Unit | Quantity |
|---|---|---|---|
| 1 | Concrete Cylinder Compressive Strength | MPa | 35 |
| 2 | Yield strength of reinforcing steel | MPa | 420 |
| 3 | Modulus of subgrade reaction for Foundation soil | kN/m3 | 100,0000 |
| 4 | Density of back fill soil to the abutments | kN/m3 | 18 |
| 5 | Angle of internal friction of back fill soil to the abutments | Degrees | 34 |
| 6 | Lateral earth pressure coefficient for non-integral bridge | kni | 0.44 |
| 7 | Lateral earth pressure coefficient for integral bridge | kni | 1.0 |
| 8 | Maximum Temperature variations expected | Degrees | 25 |
| 9 | Ground acceleration at rock level seismic | m/s2 | 1 |

**Source:** Author, 2024

**TABLE 13**
Basic data for non-integral bridge used in modelling, design and cost

| I.No | Description | Unit | Quantity | Remarks |
|---|---|---|---|---|
| 1 | Length of the bridge | m | 25.00 | |
| 2 | Number of girders | No | 4.00 | |
| 3 | Depth of the girder including the deck | m | 1.75 | |
| 4 | Spacing of the girders | m | 2.50 | |
| 5 | Depth of the top deck | m | 0.25 | |
| 6 | Carriage way width | m | 7.00 | Two lane vehicular bridge |
| 7 | Total width of the bridge | m | 11.00 | |
| 8 | Width of the girder | m | 0.50 | |
| 9 | Height of the abutment | m | 15.00 | |
| 10 | Number of diaphragm beams | No | 3.00 | |
| 11 | Width of the walk way | m | 1.50 | Both Sides |

**Source:** Author, 2024

**TABLE 14**
Basic data for integral bridge used in modelling, design and cost

| I.No | Description | Unit | Quantity | Remarks |
|---|---|---|---|---|
| 1 | Length of the bridge | m | 25.00 | |
| 2 | Number of girders | No | 4.00 | |
| 3 | Depth of the girder including the deck at support | m | 1.75 | |
| 4 | Depth of the girder including the deck at mid span | m | 1.00 | |
| 5 | Spacing of the girders | m | 2.50 | |
| 6 | Depth of the top deck | m | 0.25 | |
| 7 | Carriage way width | m | 7.00 | Two lane vehicular bridge |
| 8 | Total width of the bridge | m | 11.00 | |
| 9 | Width of the girder | m | 0.50 | |
| 10 | Height of the abutment | m | 15.00 | |
| 11 | Number of diaphragm beams | No | 2.00 | |
| 12 | Width of the walk way | m | 1.50 | Both Sides |

**Source:** Author, 2024

**TABLE 15**
Ultimate design forces in the girder beams of Integral and Non-integral Bridges of 25m span and 15m high abutments obtained from finite element analysis

| II. No | Description | Unit | Non-integral Bridge | Integral Bridge |
|---|---|---|---|---|
| 1 | Maximum positive bending at mid span | kNm | 9,656 | 3,120 |
| 2 | Maximum negative Bending at support | kNm | 0.0 | 6,041 |
| 3 | Maximum torsional moment | kNm | 249 | 224 |
| 4 | Maximum Shear Force at support | kN | 1,728 | 1,672 |

**Source:** Author, 2024

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**TABLE 16**
Ultimate design forces in the abutment wall of integral and non-integral bridges of 25m span and 15m high abutments obtained from finite element analysis

| I. No | Description | Unit | Non-integral Bridge | Integral Bridge |
|---|---|---|---|---|
| 1 | Maximum ultimate negative bending moment at top of the abutment.(fill side tension) | kNm/m | 0.0 | 3,625 |
| 2 | Maximum ultimate negative bending moment at bottom of the abutment.(fill side tension) | kNm/m | 2,733 | 1,125 |
| 3 | Maximum ultimate shear force at top the abutment | kN/m | 0.0 | 1,100 |
| 4 | Maximum ultimate shear force at bottom the abutment | kN/m | 1,300 | 1,170 |

**Source:** Author, 2024

**TABLE 17**
Ultimate design forces in the footing base of integral and non-integral bridges of 25m span and 15m high abutments obtained from finite element analysis

| I. No | Description | Unit | Non-integral Bridge | Integral Bridge |
|---|---|---|---|---|
| 1 | Maximum ultimate bending moment at top of the footing heel side.( tension on the top) | kNm/m | 1,555 | 685 |
| 2 | Maximum ultimate bending moment at bottom of the footing toe side.( tension on the bottom) | kNm/m | 1,568 | 695 |
| 3 | Maximum ultimate shear force | kN/m | 1,250 | 1,050 |

**Source:** Author, 2024

**TABLE 18**
Superstructure deflections at service for integral and non-integral bridges of 25m span and 15m high abutments. Cracked moment of inertia used to reflect the reality

| I. No | Description | Unit | Non-integral Bridge | Integral Bridge |
|---|---|---|---|---|
| 1 | Maximum permanent load deflection at mid span | mm | 36 | 20 |
| 2 | Maximum live load deflection at mid span | mm | 16 | 11 |
| 3 | Maximum service live load deflection at mid span | mm | 52 | 31 |

**Source:** Author, 2024

**TABLE 19**
Foundation stresses at service for integral and non-integral bridges of 25m span and 15m high abutments

| I. No | Description | Unit | Non-integral Bridge | Integral Bridge |
|---|---|---|---|---|
| 1 | Maximum foundation stress at service | $kN/m^2$ | 36 | 20 |

**Source:** Author, 2024

**TABLE 20**
Estimated concrete and steel reinforcements for integral and non-integral bridges of 25m span and 15m high abutments

| I. No | Description | Unit | Non-integral Bridge | Integral Bridge |
|---|---|---|---|---|
| 1 | Concrete C35/45 in super-structure | $m^3$ | 231 | 203 |
| 2 | Concrete C35/45 in sub-structure | $m^3$ | 1,227 | 963 |
| 3 | Total concrete C35/45 m3 | $m^3$ | 1,458 | 1,166 |
| 4 | High yield strength Fy=500MPa in super-structure | Tons | 33.9 | 30.6 |
| 5 | High yield strength Fy=500MPa in sub-structure | Tons | 110.4 | 87.4 |
| | Total reinforcement | Tons | 144.3 | 118.0 |

**Source:** Author, 2024

**Midas Civil Analytical Computations-Integral Bridges Models**

**Figure 18** shows the 3D model of the integral bridge model used in the MIDAS CIVIL finite element analysis. **Figure 19** to **Figure 25** show the results obtained from the finite element analysis.

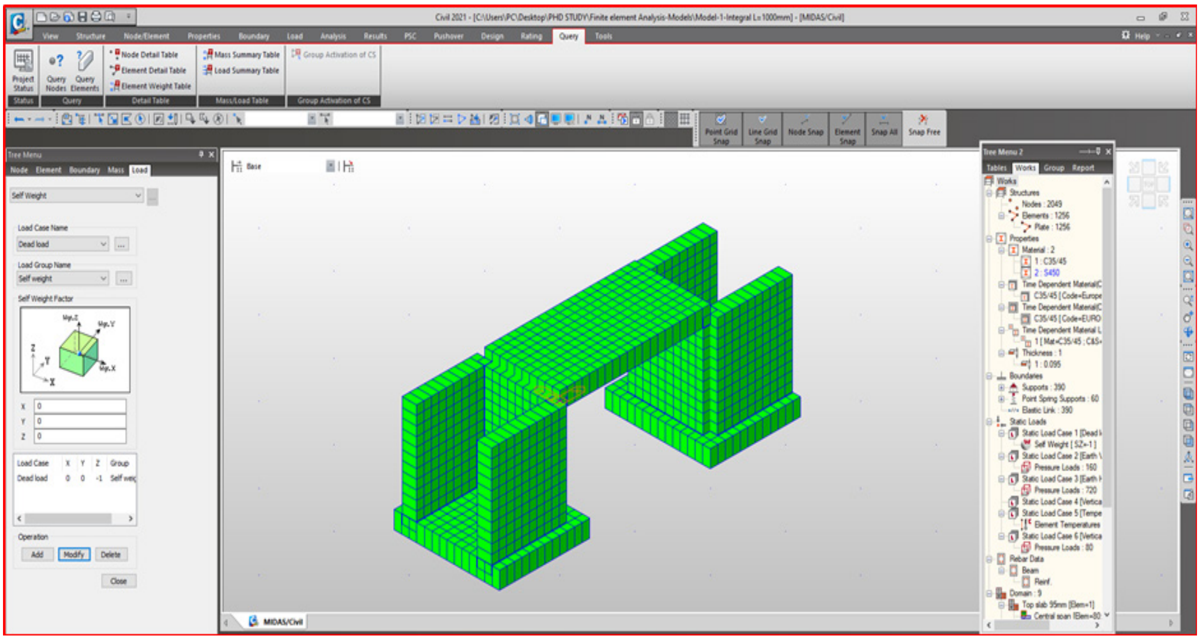

**FIGURE 18**
3D Model of integral bridge for MIDAS CIVIL finite element analysis
**Source:** Author, 2024

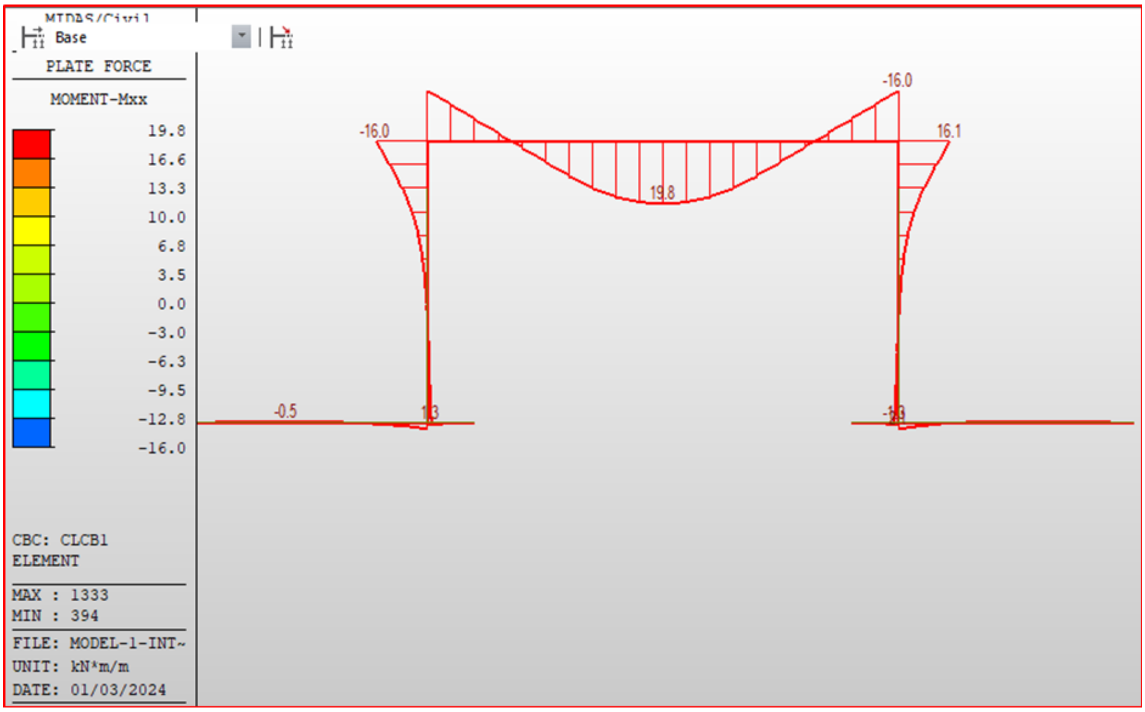


**FIGURE 19**
Bending moment with vertical load of 89.9kN L=1m integral. The yield moment 13.4kNm>19.8*0.5kN-m=9.9kNm
**Source:** Author, 2024

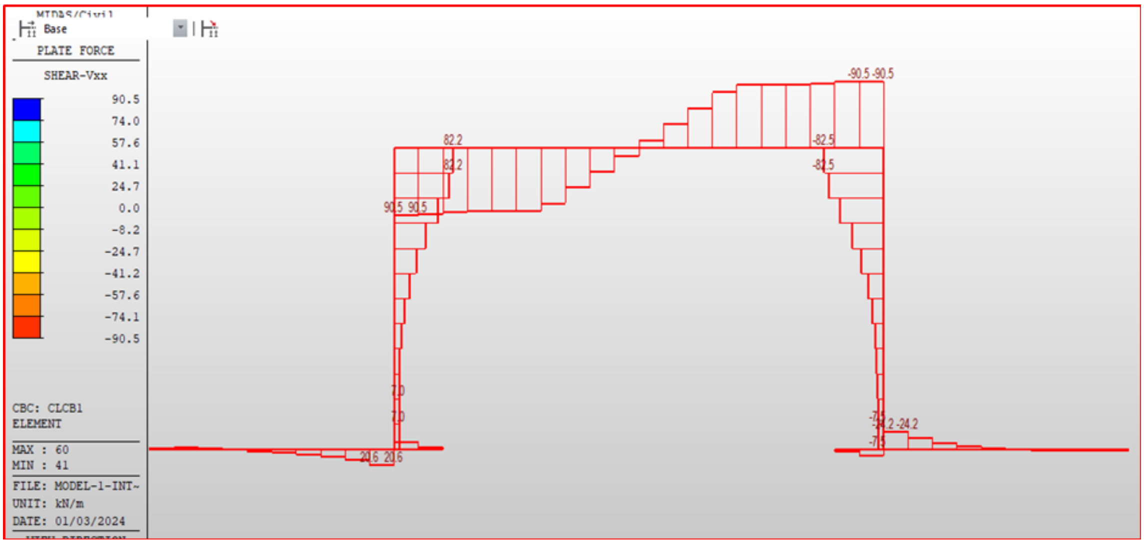


**FIGURE 20**
Shear force with vertical load of 89.9kN L=1m integral. Failure shear force 45.6kN~90.5*0.5kN= 45.3kN shear governs
**Source:** Author, 2024

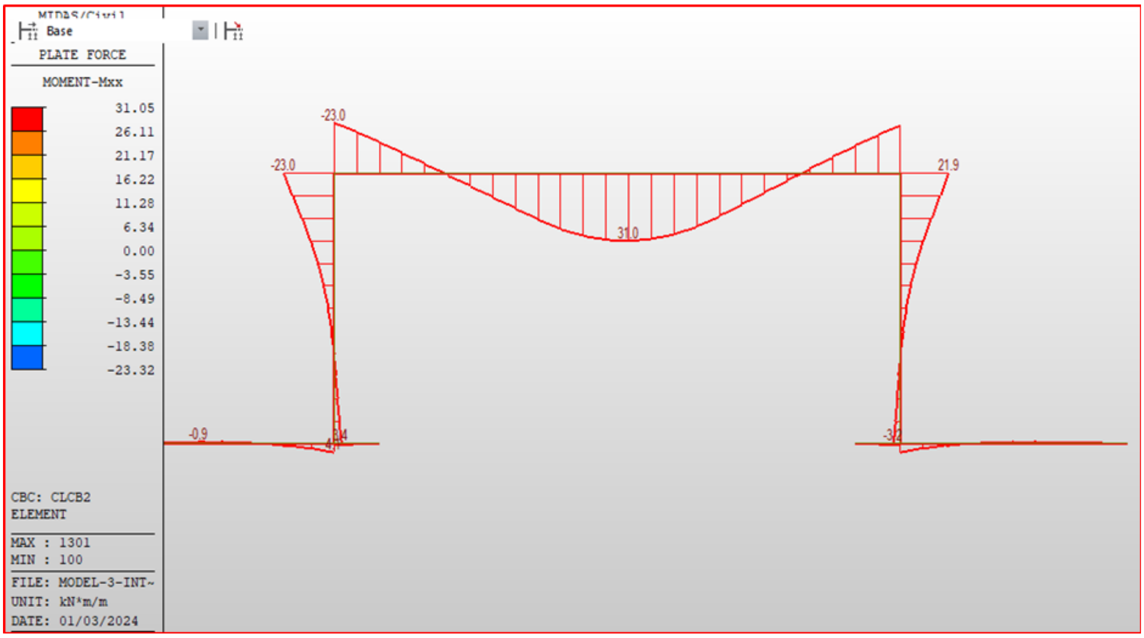


**FIGURE 21**
Bending moment with vertical load of 105kN L=1.25m integral. The yield moment 18.5kNm>31*0.5kN-m=15.5kNm
**Source:** Author, 2024

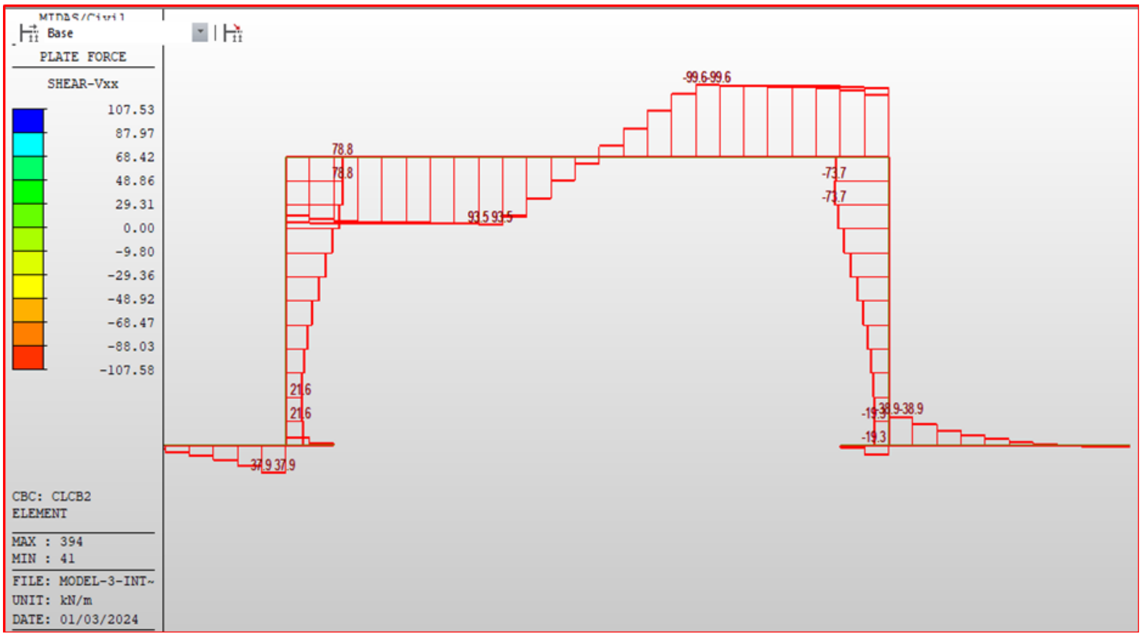


**FIGURE 22**
Shear force with vertical load of 105kN L=1.25m integral. Failure shear force 53.3kN~107*0.5kN= 53.5kN shear governs
**Source:** Author, 2024

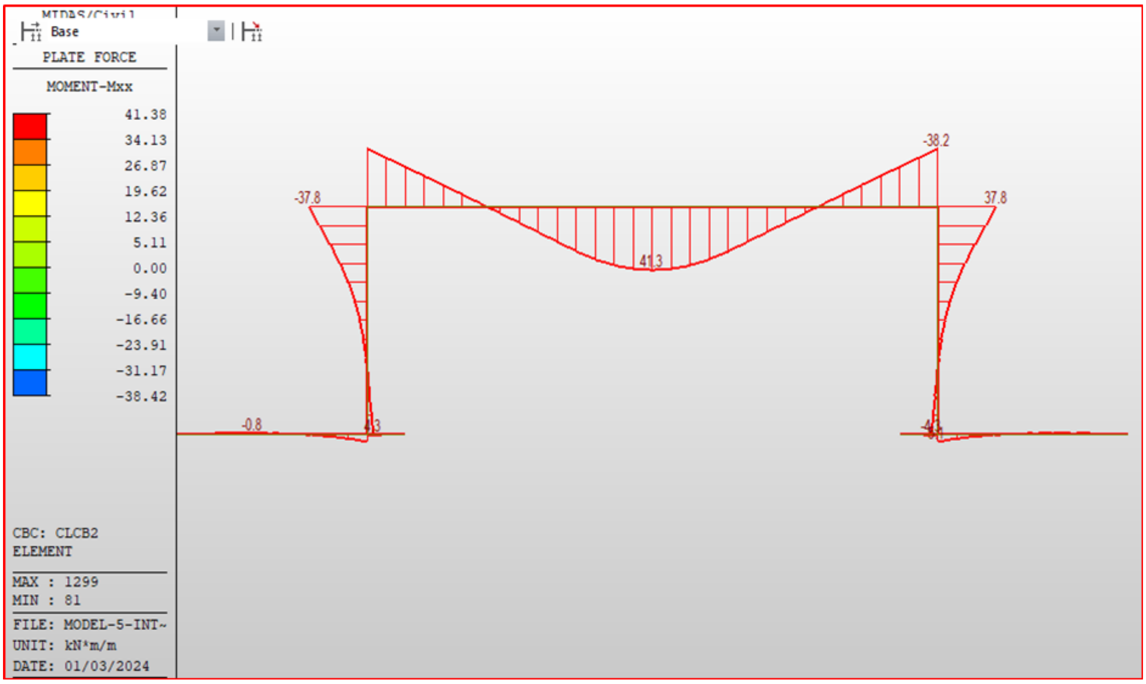


**FIGURE 23**
Bending moment with vertical load of 124.7kN L=1.50m integral. The yield moment 26.0kN-m>41.4*0.5kNm=20.7kNm
**Source:** Author, 2024

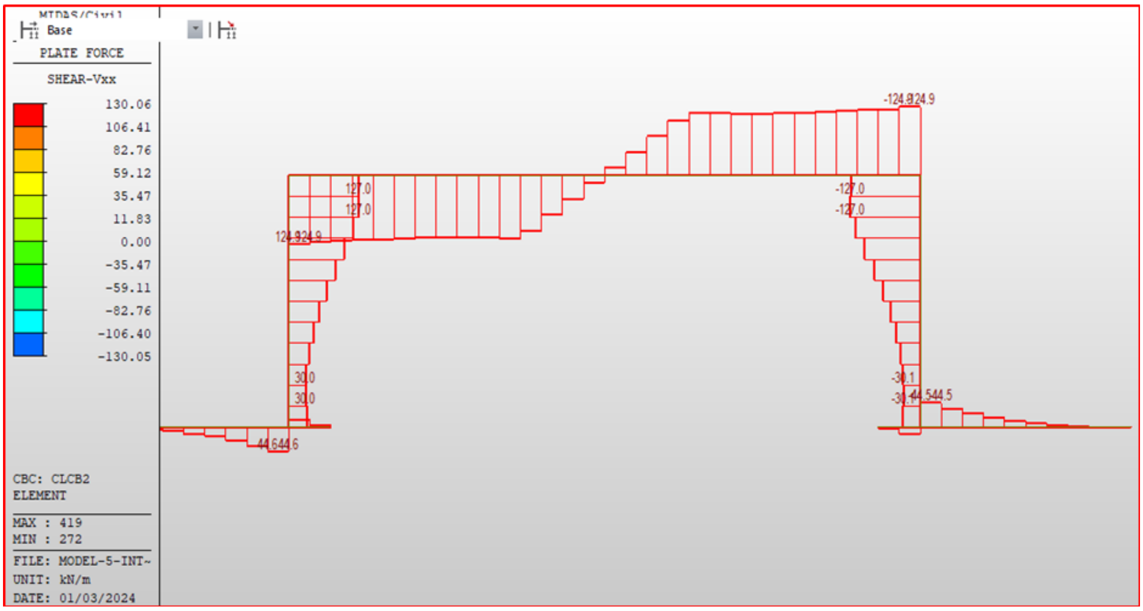


**FIGURE 24**
Shear force with vertical load of 124.7kN L=1.50m integral. Failure shear force 63.5kN~130*0.5kN= 65.0kN shear governs
**Source:** Author, 2024

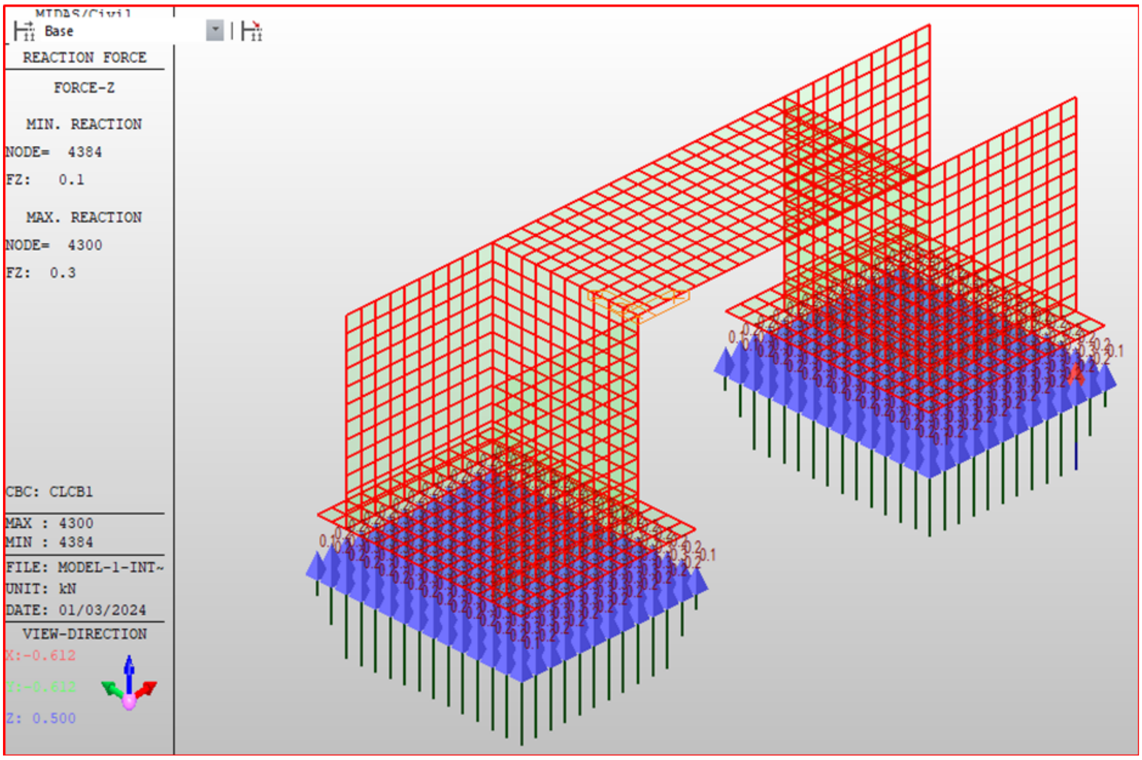


**FIGURE 25**
Foundation stress for the vertical load of 89.9kN L=1m integral
Stress=0.3/ (0.05*0.05) kN/m2=120kN/m2
**Source:** Author, 2024

**Midas Civil Analytical Computations-Non-Integral Bridges**

**Figure 26** shows the 3D model of the integral bridge model used in the MIDAS CIVIL finite element analysis. **Figure 27** to **Figure 33** show the results obtained from the finite element analysis.

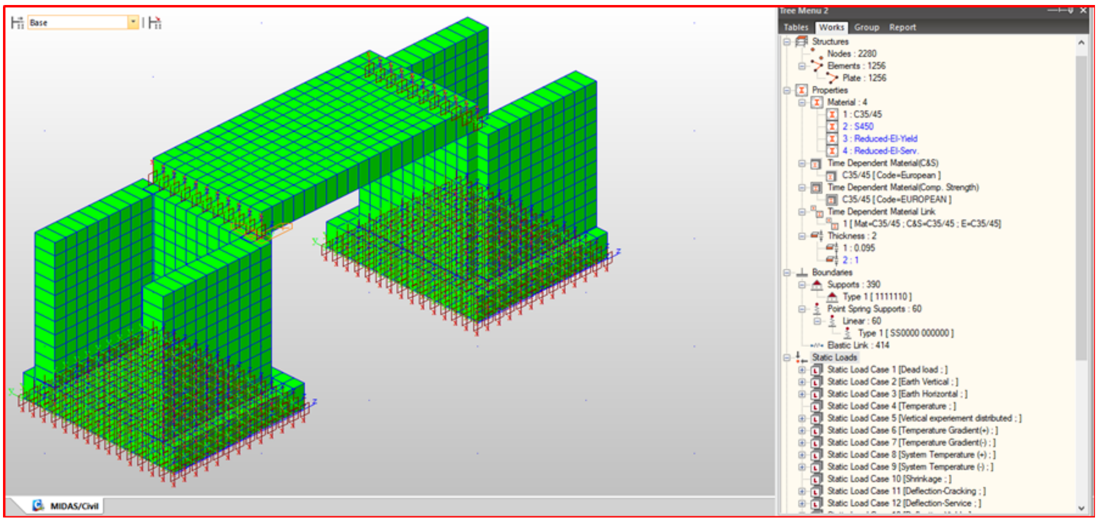

**FIGURE 26**
3D Model of non-integral bridge for MIDAS CIVIL finite element analysis
**Source:** Author, 2024

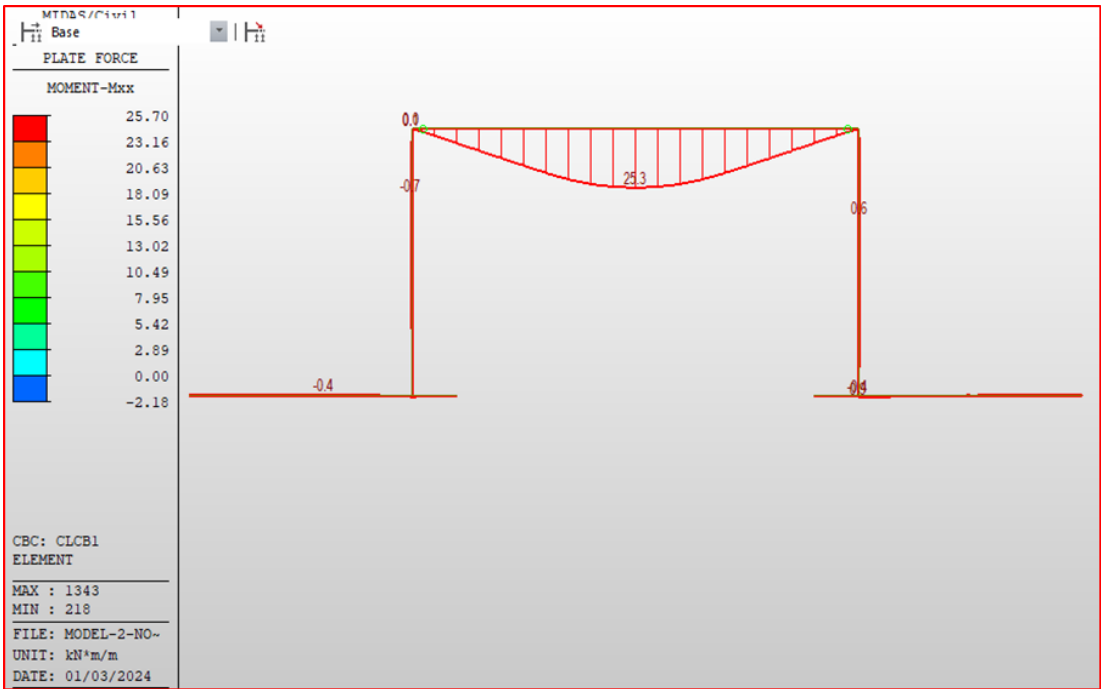


**FIGURE 27**
Bending moment with Vertical load of 63kN L=1m Non-integral. The yield moment 13.4kN-m~25.7*0.5kNm=13kNm
**Source:** Author, 2024

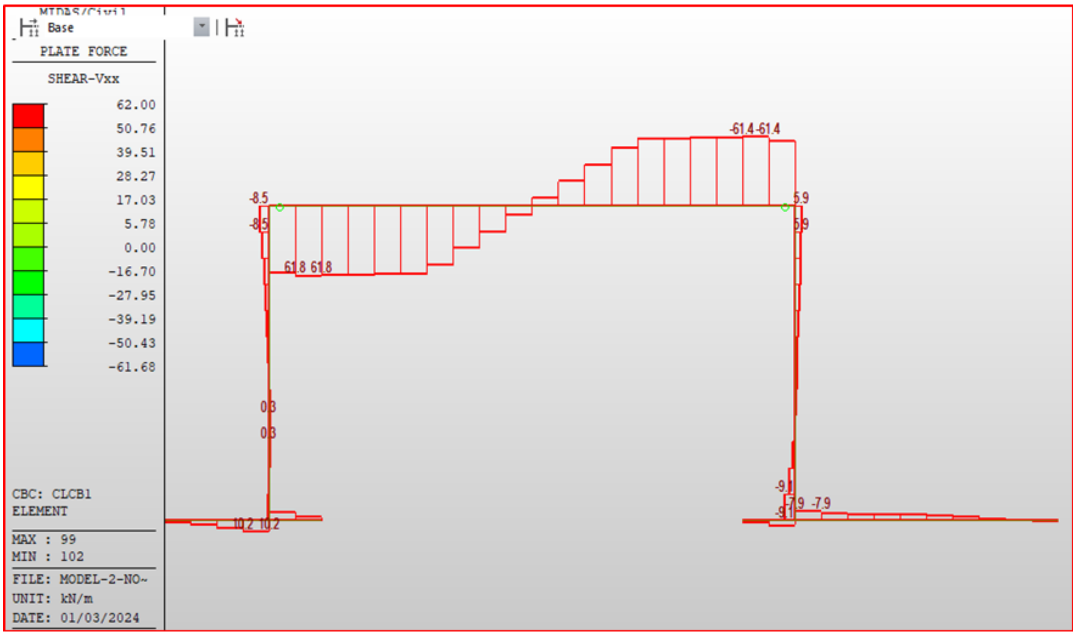


**FIGURE 28**
Shear force with Vertical load of 63kN L=1m Non-integral. Failure shear force 45.6kN>62*0.5kN= 31kN. Flexure governs
**Source:** Author, 2024

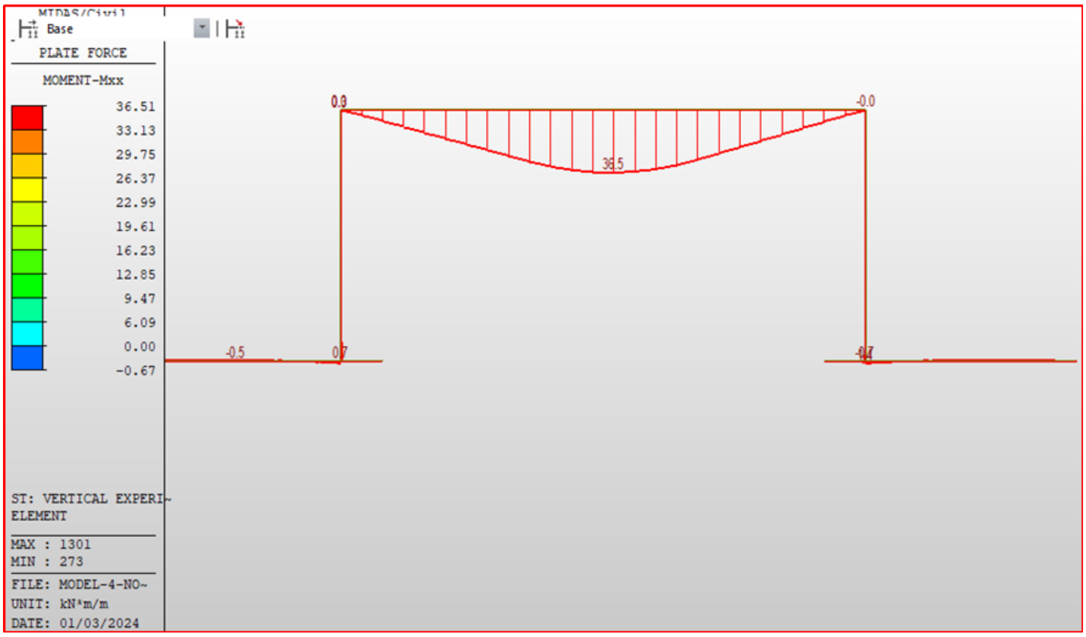


**FIGURE 29**
Bending moment with Vertical load of 70kN L=1.25m Non-integral. The yield moment 18.5kN-m~36.5*0.5kNm=18.3kNm
**Source:** Author, 2024

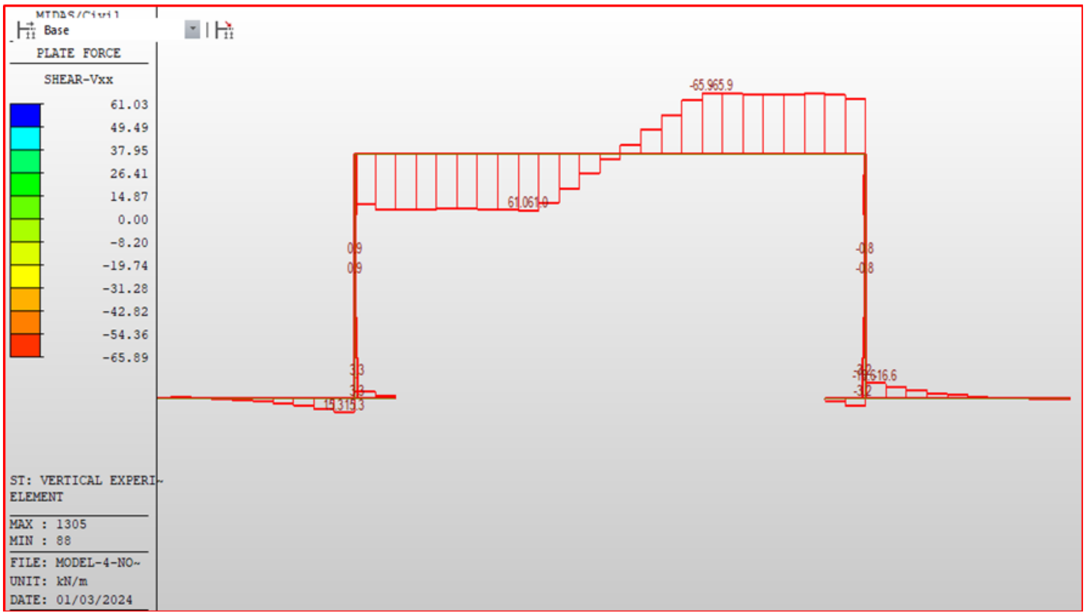


**FIGURE 30**
Shear force with Vertical load of 70kN L=1.25m Integral. Failure shear force 53.3kN>65.0*0.5kN= 32.5kN flexure governs
**Source:** Author, 2024

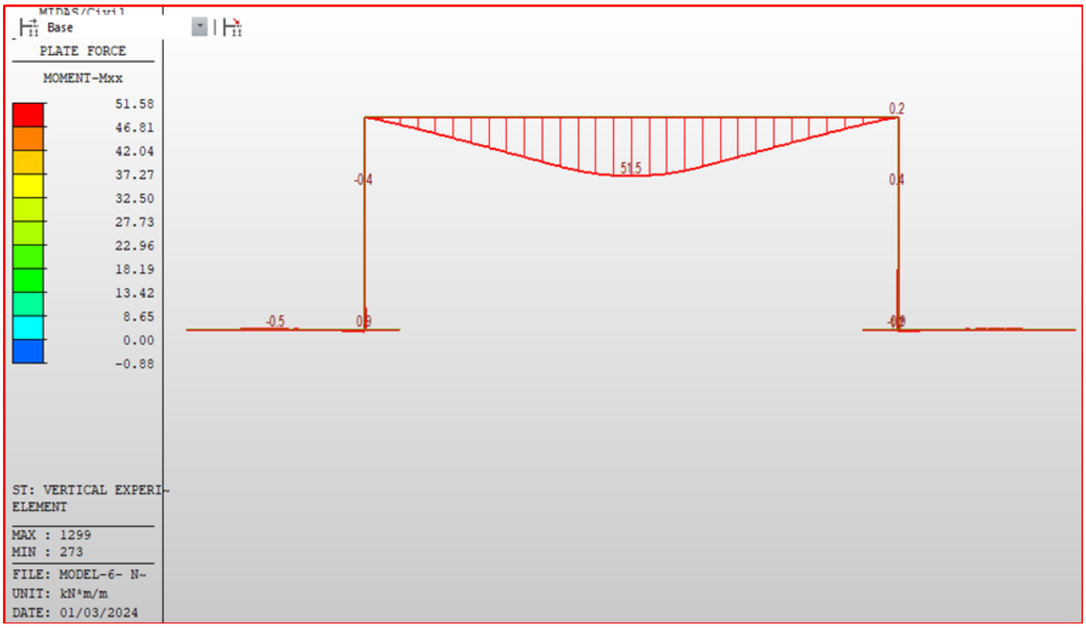


**FIGURE 31**
Bending moment with Vertical load of 84kN L=1.50m Non-integral. The yield moment 26.0kN-m~52*0.5kNm=26kNm
**Source:** Author, 2024

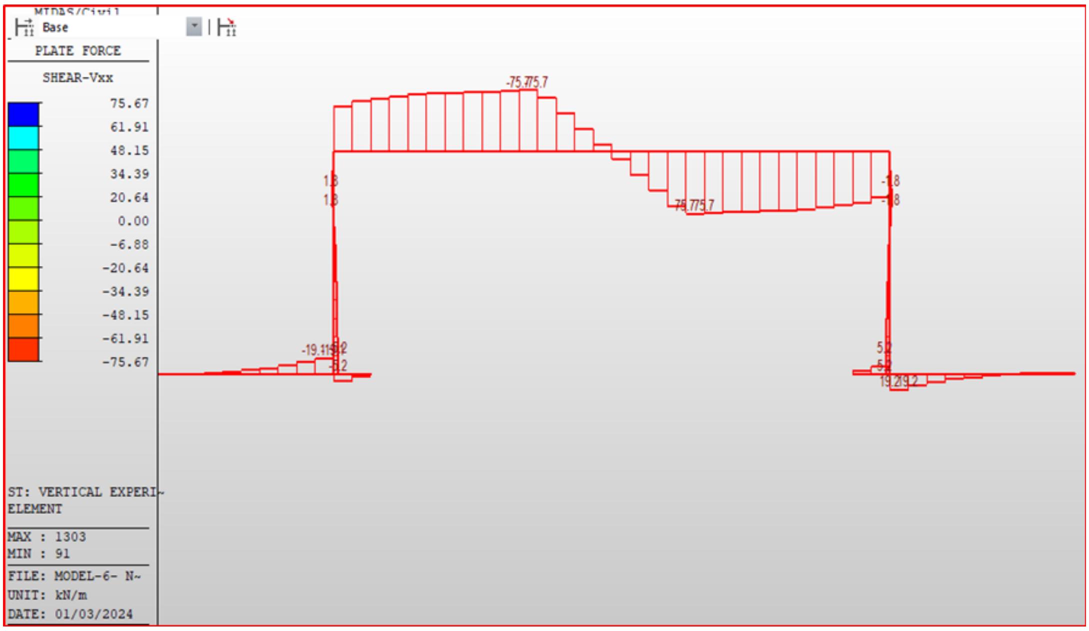


**FIGURE 32**
Shear force with Vertical load of 84kN L=1.50m Integral. Failure shear force 63.5kN>75.7*0.5kN= 37.9kN flexure governs
**Source:** Author, 2024

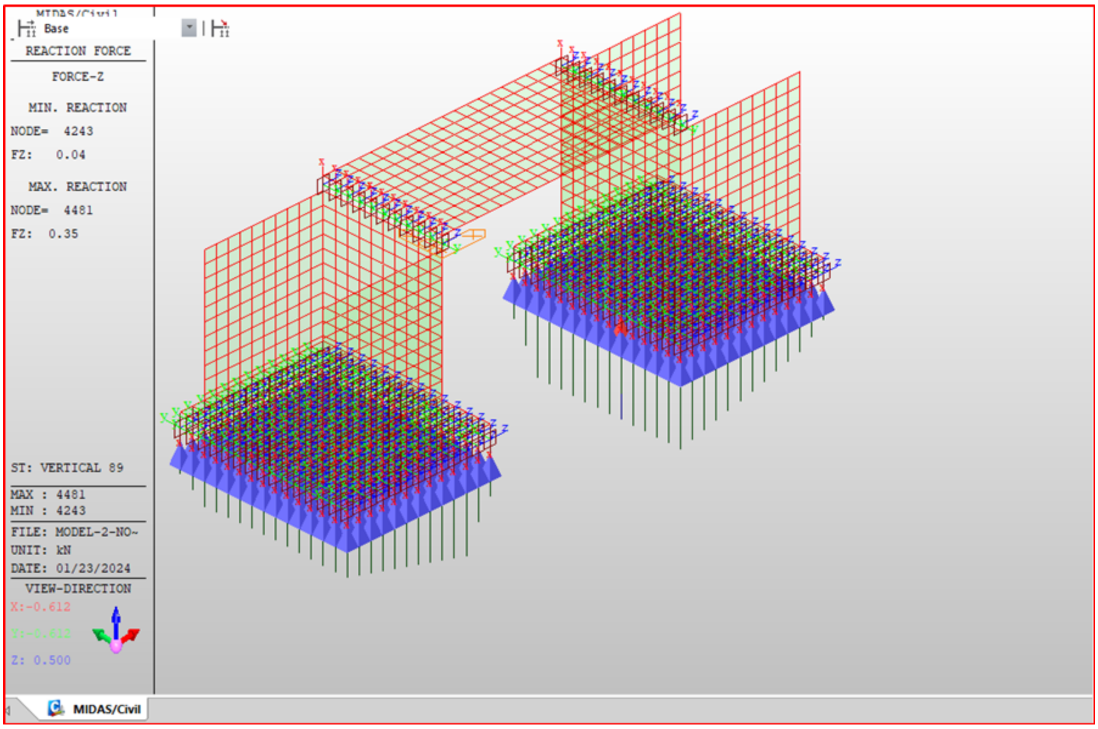


**FIGURE 33**
Foundation stress for the vertical load of 89.9kN L=1m Integral Stress=0.35/ (0.05*0.05) kN/m2=140kN/m2
**Source:** Author, 2024

**Midas Civil Analytical Computations-Non-Integral Girder Bridge Length 25m**

The modelling analysis and design of the 25m long non-integral bridge done using MIDAS CIVIL finite element analysis and presented. Drawings produced to calculate the bill of quantities and the cost. **Figure 34** shows the 3D model of the 25m long non-integral bridge with 15m abutment height. **Figure 35** to **Figure 43** show the results obtained from the finite element analysis.

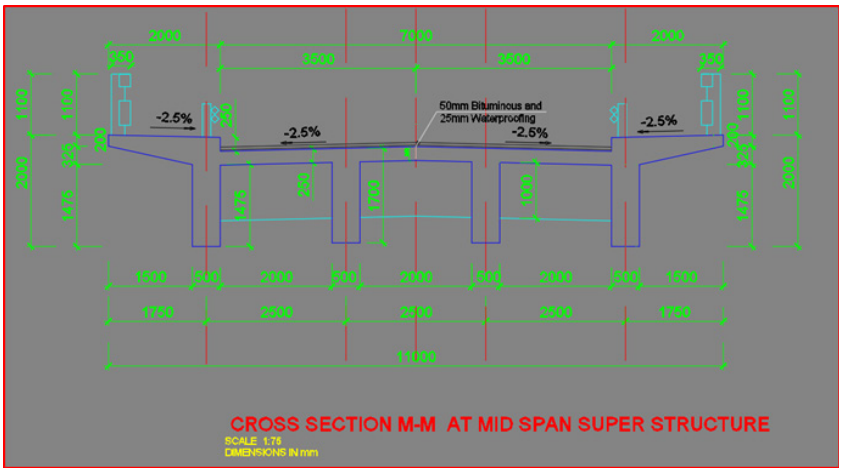


**FIGURE 34**
Cross section of Non-integral bridge with length of bridge=25m one span
**Source:** Author, 2024

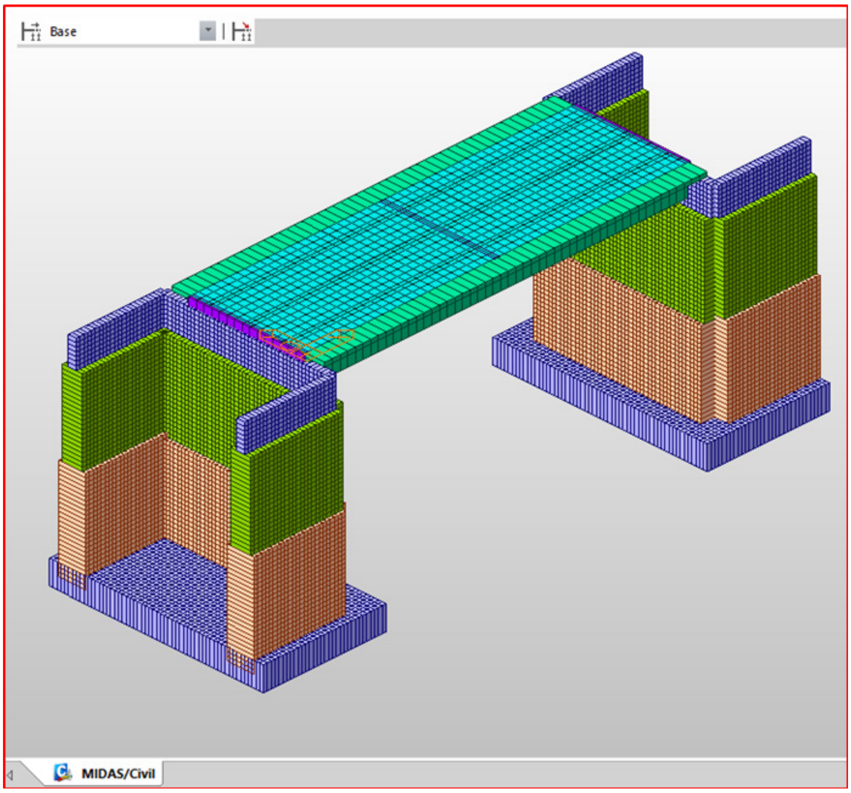


**FIGURE 35**
3D Model of Non-integral bridge Length of bridge=25m one span
**Source:** Author, 2024

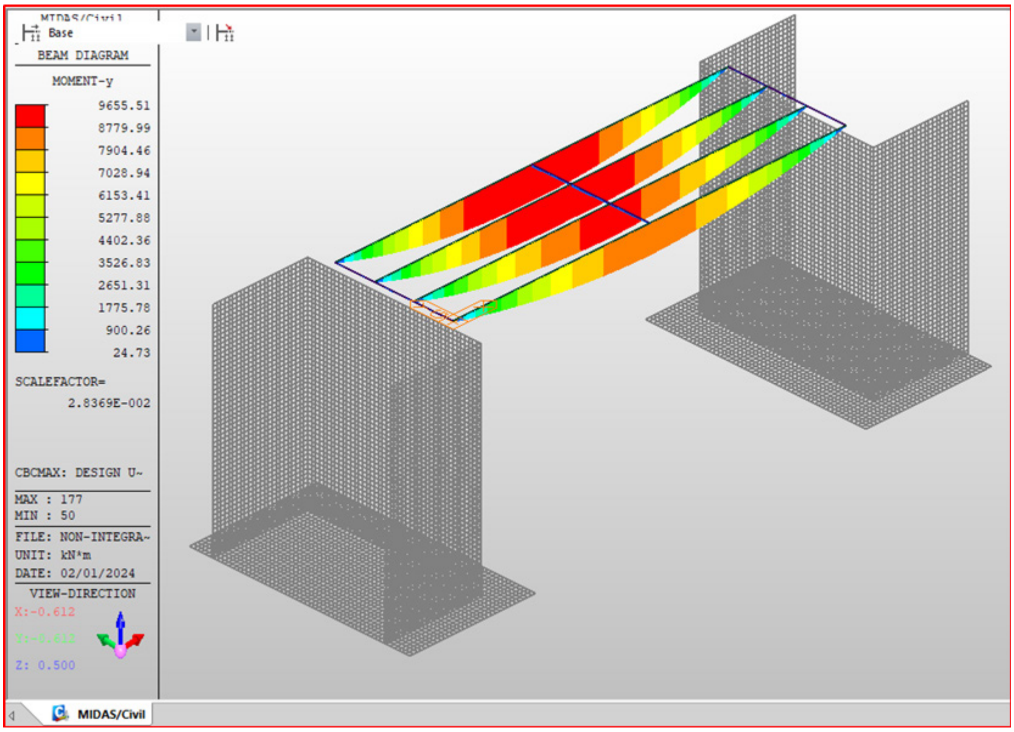


**FIGURE 36**
Ultimate limit state Design Bending moment Non-integral length of the bridge 25m. Maximum design positive bending moment at mid span central beam=9656kNm
**Source:** Author, 2024

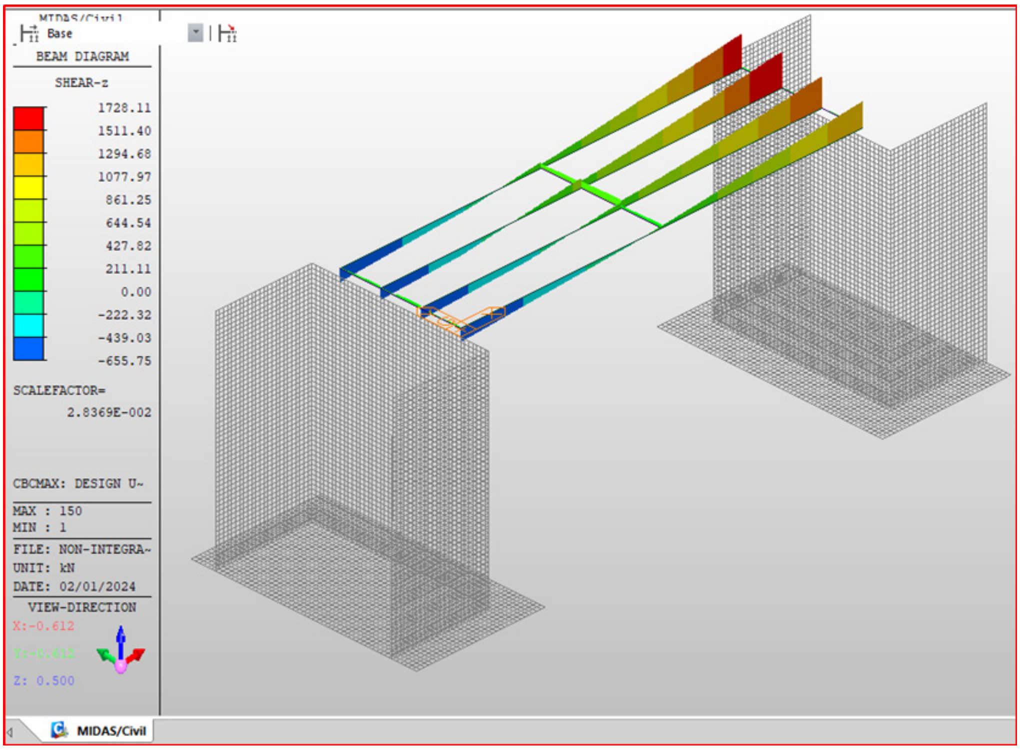


**FIGURE 37**
Ultimate limit state Design Shear force Non-integral length of the bridge 25m. Maximum design shear force at support=1728kN
**Source:** Author, 2024

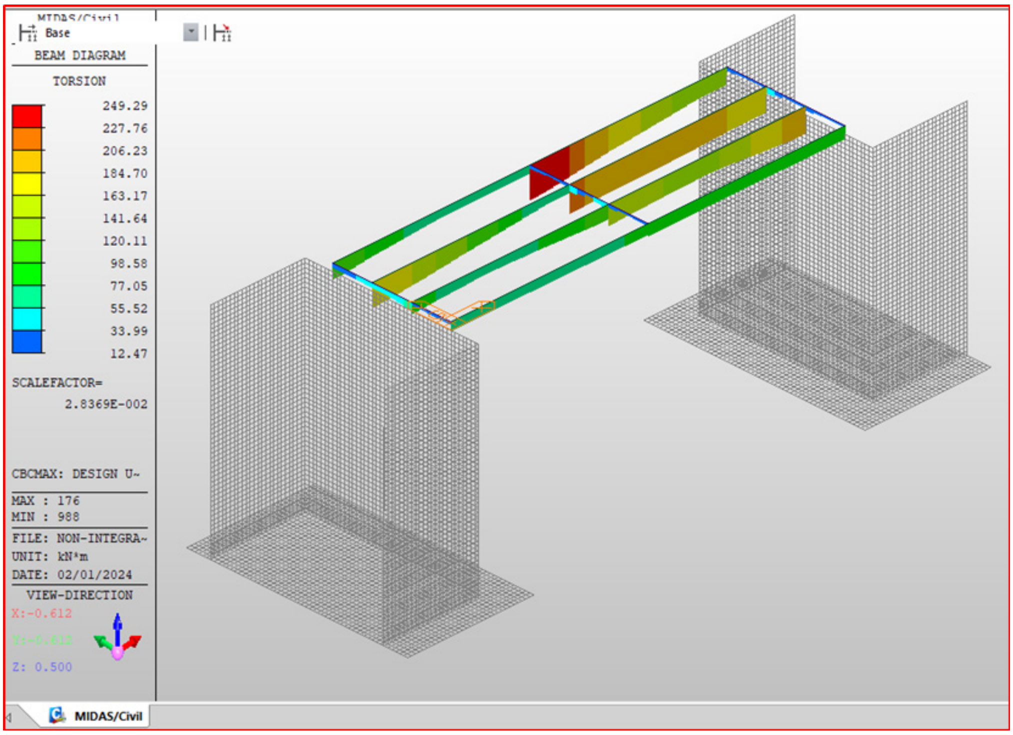


**FIGURE 38**
Ultimate limit state Design Bending Torsional moment Non-integral length of the bridge 25m. Maximum design torsional moment =249kNm
**Source:** Author, 2024

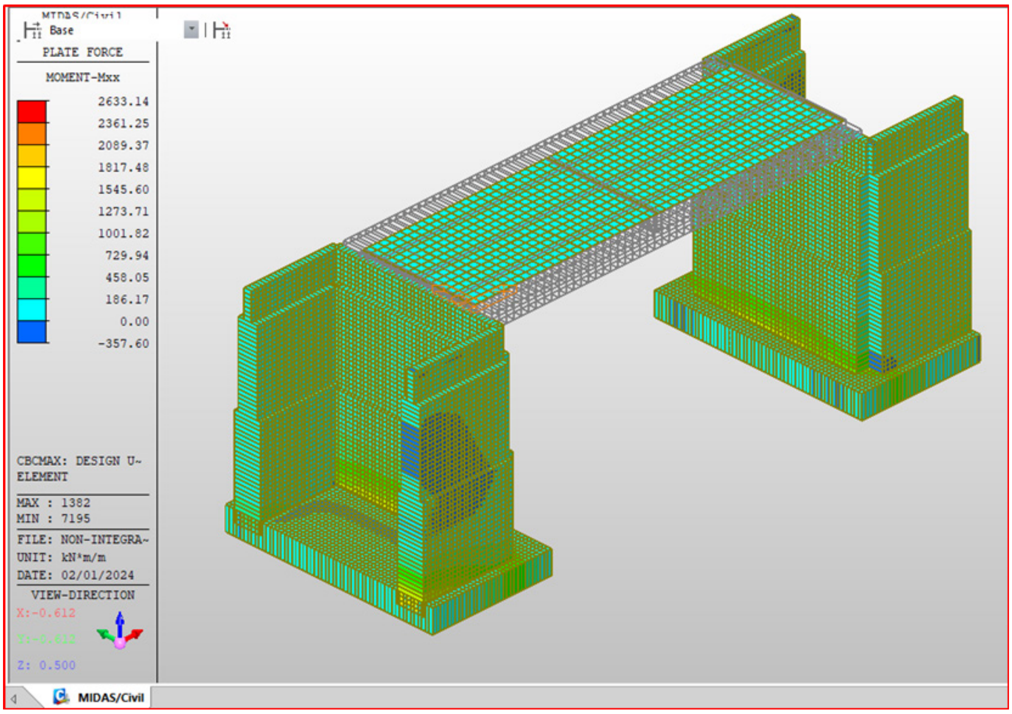


**FIGURE 39**
Ultimate limit state Design Bending Mxx abutment walls and wing walls Non-integral length of the bridge 25m. Maximum design moment =2633kNm/m
**Source:** Author, 2024

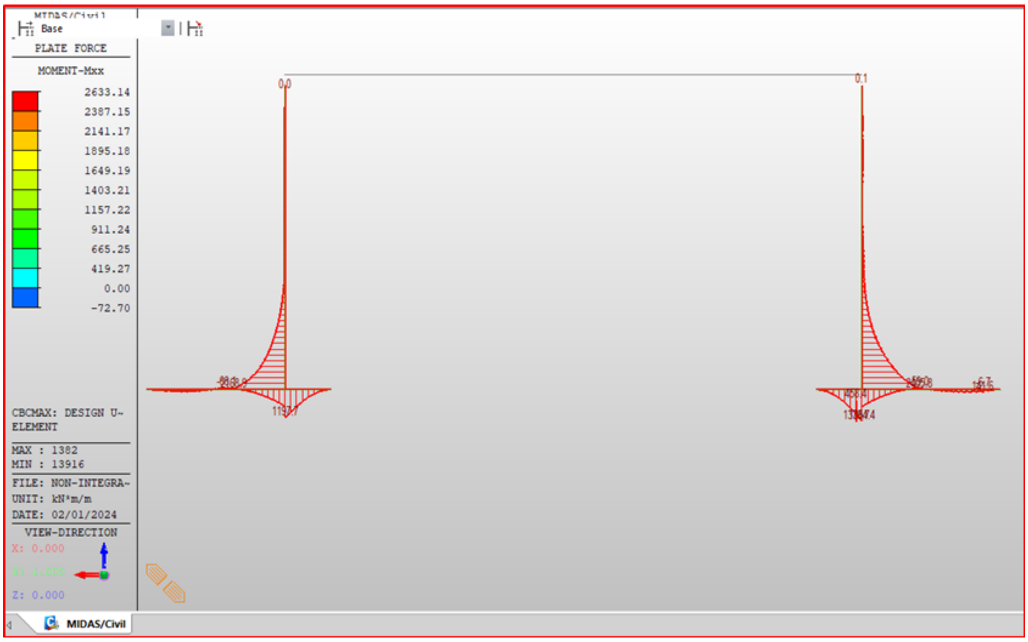


**FIGURE 40**
Ultimate limit state Design Bending Mxx abutment walls and wing walls Non-integral length of the bridge 25m. Maximum design moment =2633kNm/m
**Source:** Author, 2024

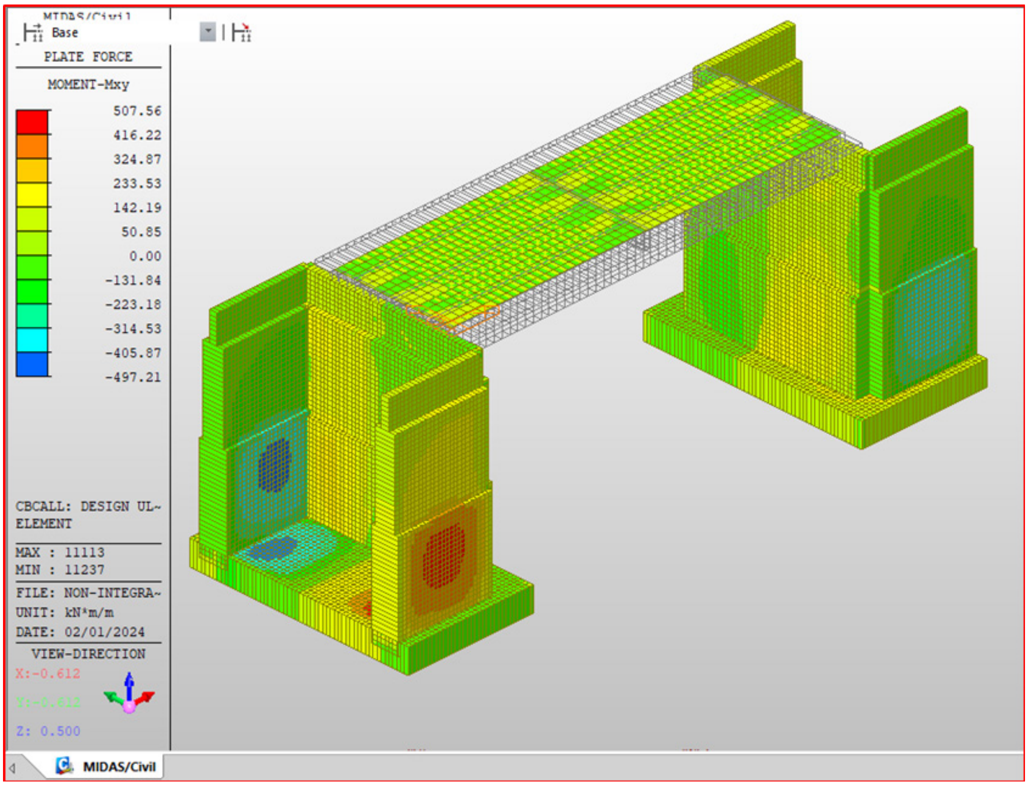


**FIGURE 41**
Ultimate limit state Design Torsional moment Mxy abutment walls and wing walls Non-integral length of the bridge 25m. Maximum torsional design moment =507kNm/m
**Source:** Author, 2024

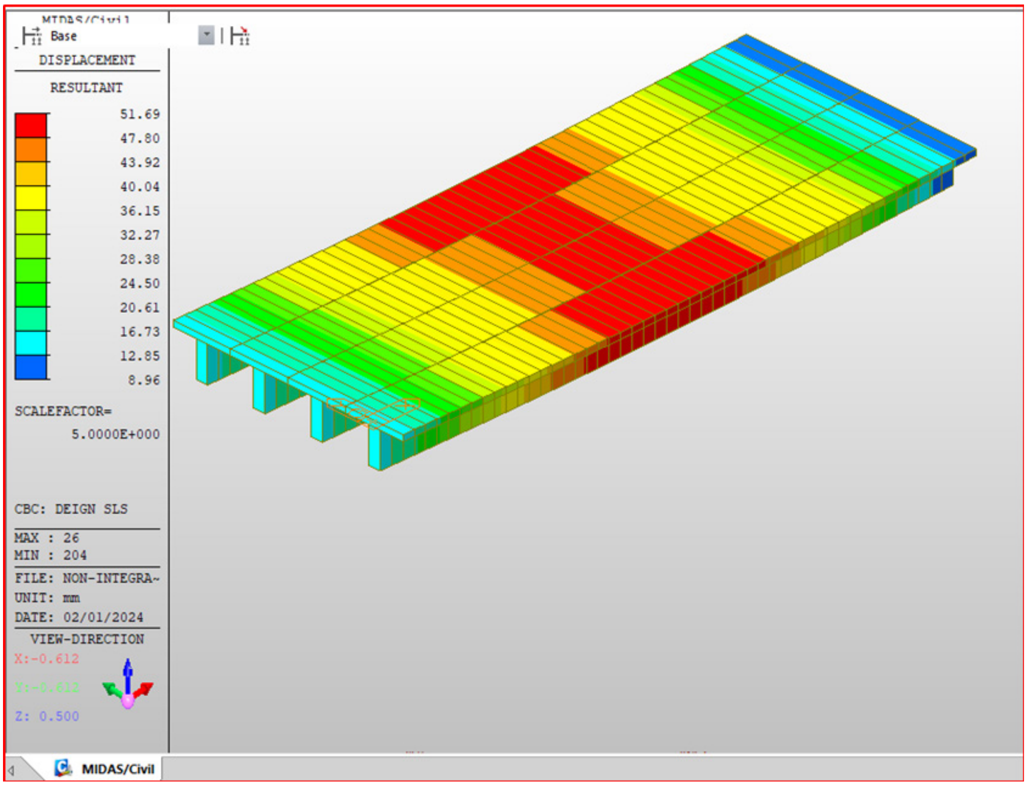


**FIGURE 42**
Computed service load deflections of 25m span Girder Bridge using MIDAS CIVIL Finite element analysis, the moment of inertia used is the cracked moment of inertia. Calculated deflection 52mm less than the allowable deflection of about 75mm
**Source:** Author, 2024

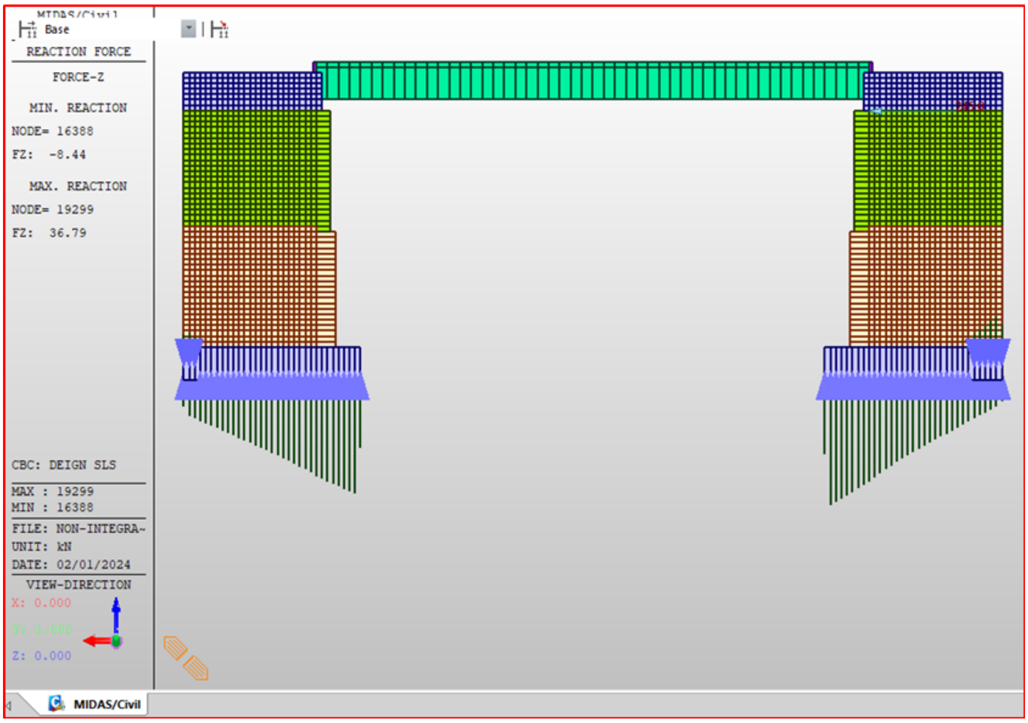


**FIGURE 43**
7Foundation stress at service load Non- integral bridge length 25m Foundation Stress=36.79/(0.25*0.25) kN/m2=589kN/m2. Mesh spacing 0.25mx0.25m
**Source:** Author, 2024

**Midas Civil Analytical Computations-Integral Girder Bridge Length 25m**

The modelling analysis and design of the 25m long integral bridge done using MIDAS CIVIL finite element analysis and presented. **Figure 44** shows the 3D model of the 25m long non-integral bridge with 15m abutment height.

**Figure 44** to **Figure 51** show the results obtained from the finite element analysis.

**Cost Comparisions between Integral and Non-Integral Bridges L=25m**

**Table 21** shows the estimated cost for 25m long non integral bridge while **Table 22** shows the estimated cost for 25m long integral bridge. The decrease of cost by 19.2% for integral bridge as compared to non-integral bridges with the same length of 25m and height of 15m obtained .Similarly similar computation were done for 15m,20m and 22.5m spans and the results are used to prepare empirical formulas to compare cost versus length **Table 23**.

**Figure 52** shows the decrease in the cost for integral bridge compared to non-integral bridges of different length. A decrease of 19.2% to 20.0% observed as per the recent market prices and the design made.

The numerical results obtained in regards to bending moments, shear forces, torsional forces show that it is in consistence with the theories of load distribution among structural members.

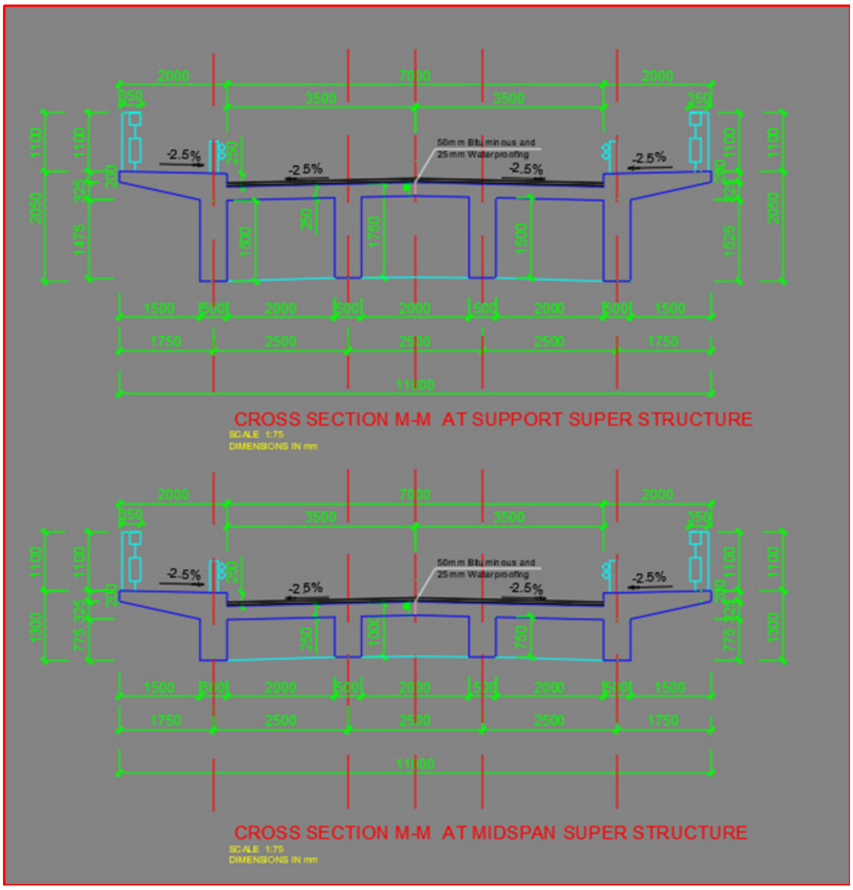


**FIGURE 44**
Cross section of Integral bridge with length of bridge=25m one span
**Source:** Author, 2024

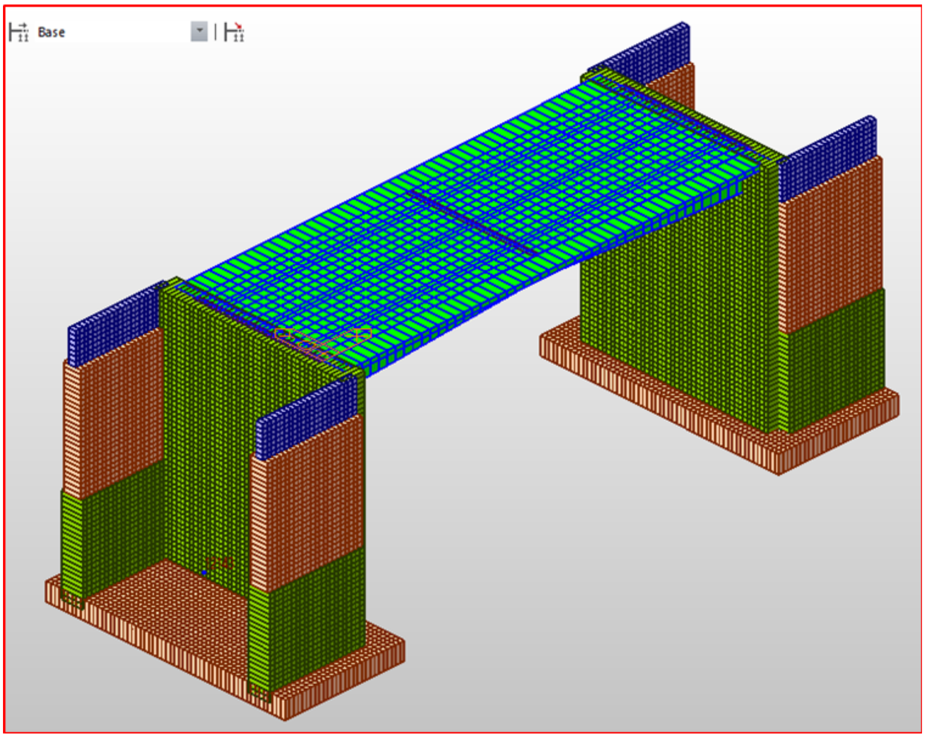


**FIGURE 45**
3D Model of Integral bridge Length of bridge=25m one span
**Source:** Author, 2024

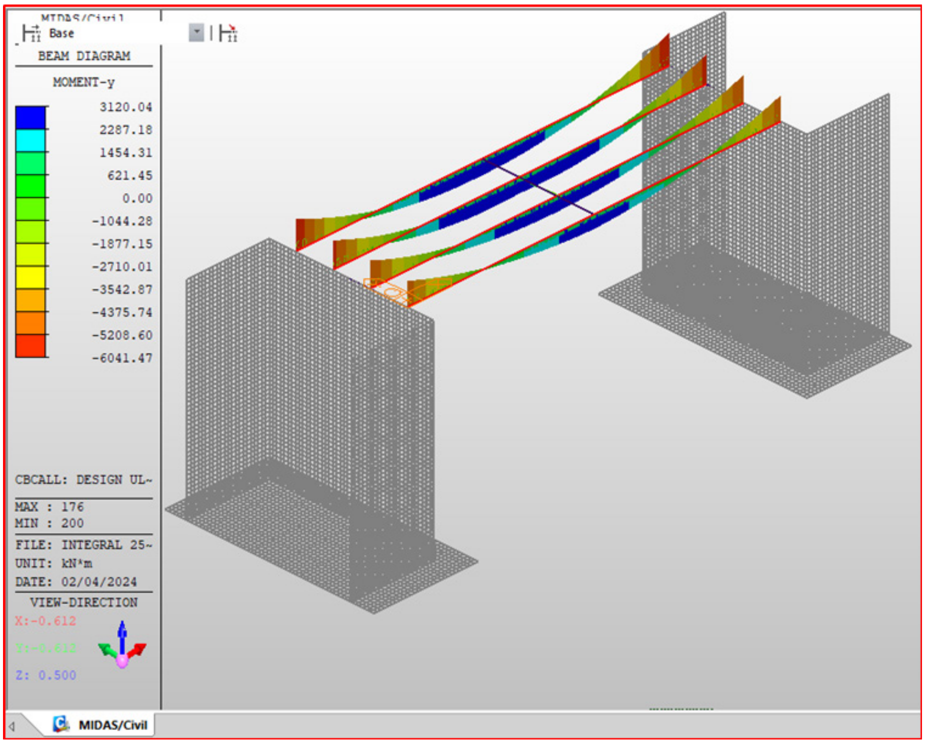


**FIGURE 46**
Ultimate limit state Design Bending moment Integral length of the bridge 25m. Maximum design positive bending moment at mid span central beam=3120kNm and maximum design negative moment of 6042kNm
**Source:** Author, 2024

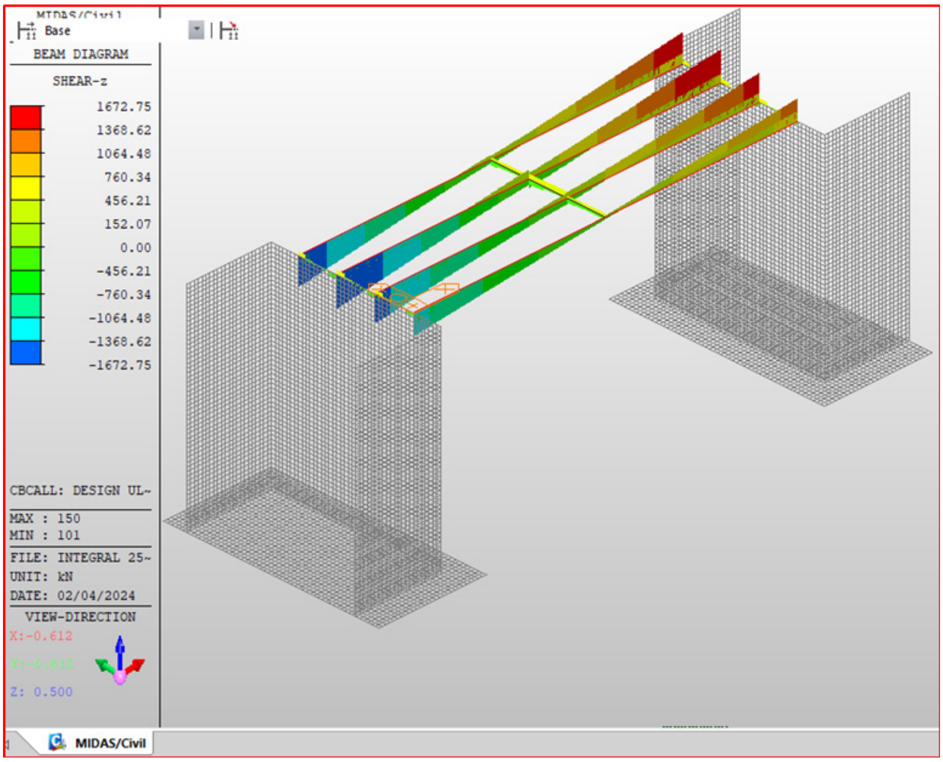


**FIGURE 47**
Ultimate limit state Design Shear force Integral length of the bridge 25m. Maximum design shear force at support=1672kN
**Source:** Author, 2024

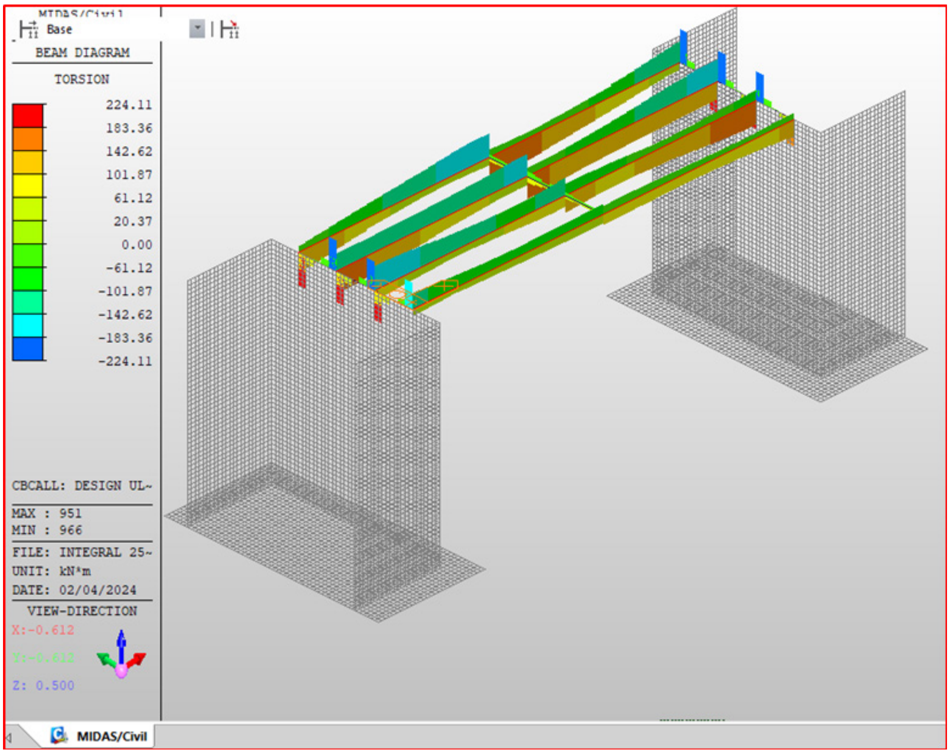


**FIGURE 48**
Ultimate limit state Design Bending Torsional moment Integral length of the bridge 25m. Maximum design torsional moment =224kNm
**Source:** Author, 2024

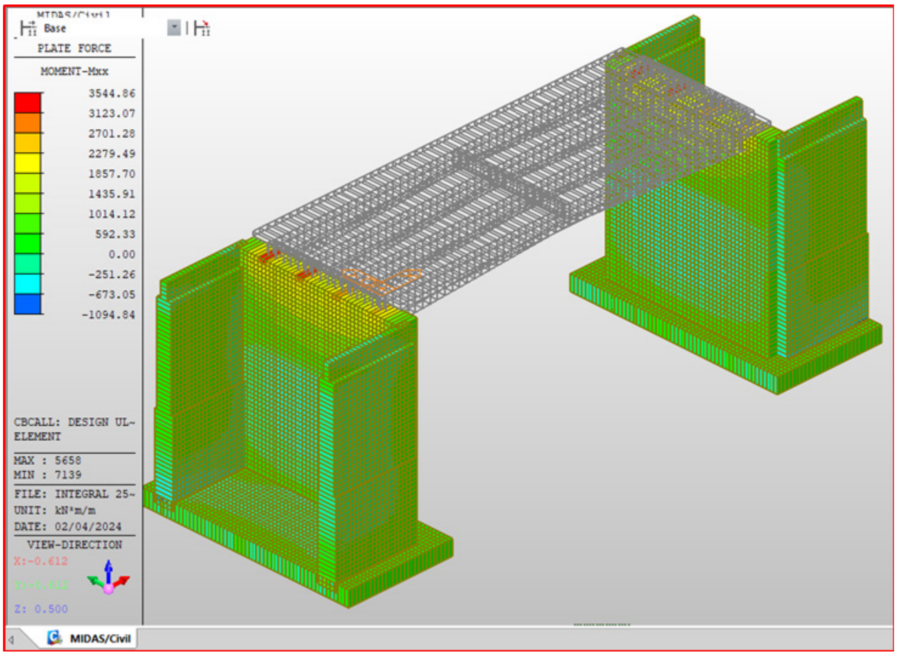


**FIGURE 49**
Ultimate limit state Design Bending Mxx abutment walls and wing walls Integral length of the bridge 25m
**Source:** Author, 2024

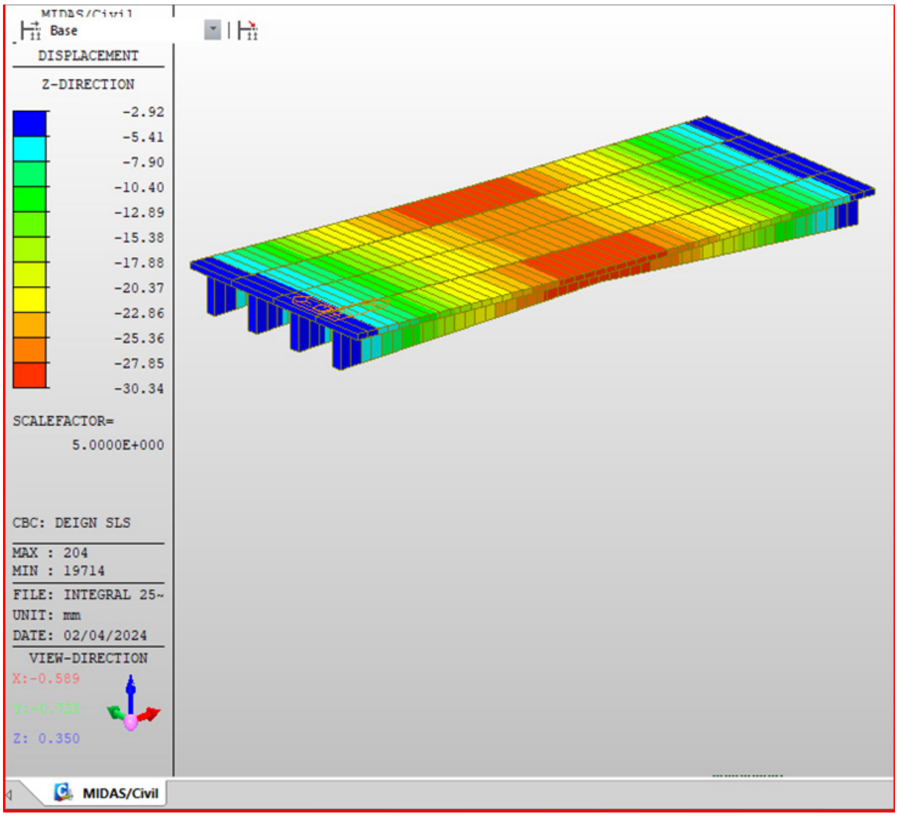


**FIGURE 50**
Computed service load deflections of 25m span integral Girder Bridge using MIDAS CIVIL Finite element analysis, the moment of inertia used is the cracked moment of inertia. Calculated deflection 30mm less than the allowable deflection of about 75mm
**Source:** Author, 2024

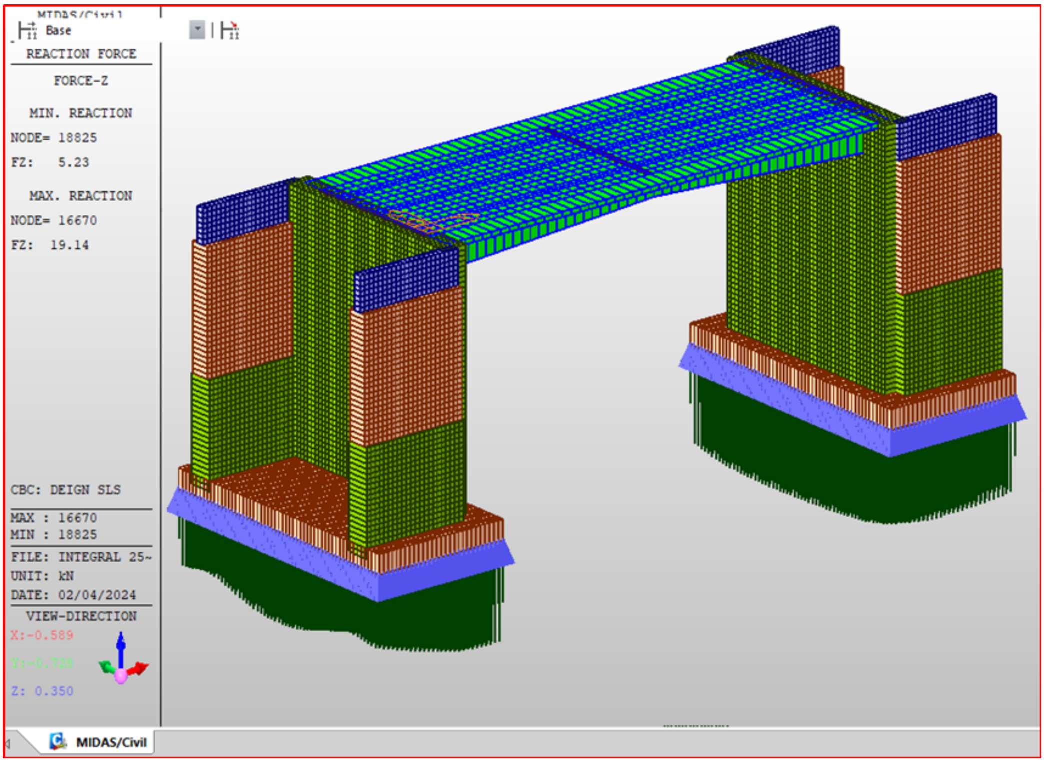


**FIGURE 51**
Foundation stress at service load Integral bridge length 25mFoundation Stress=19.14/ (0.25*0.25) kN/m2=306kN/m2. Mesh spacing 0.25mx0.25m
**Source:** Author, 2024

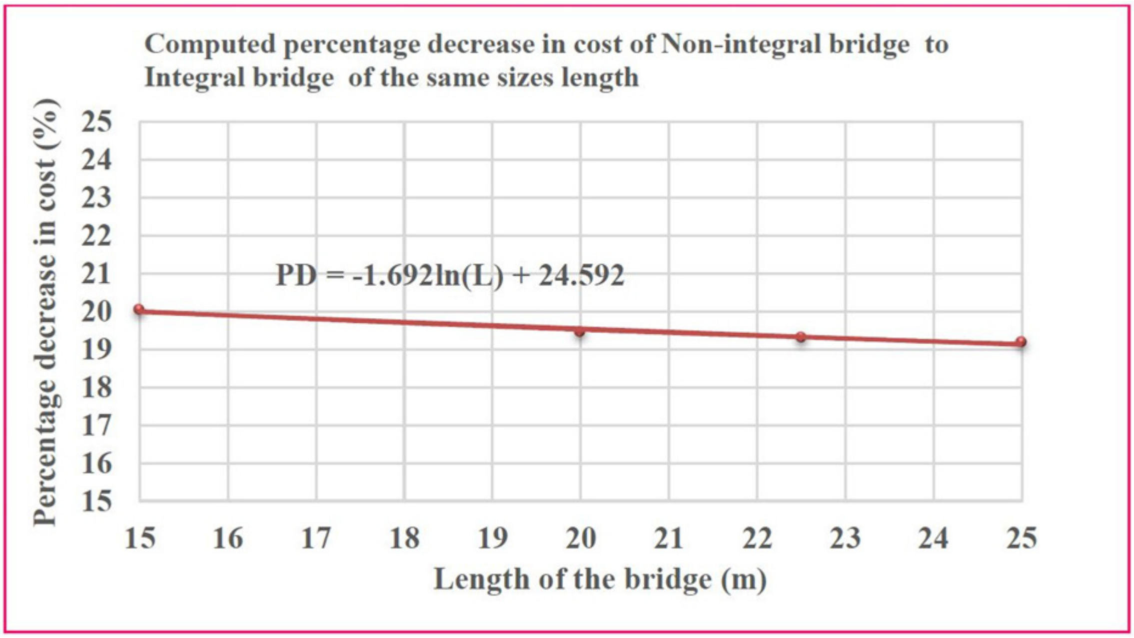


**FIGURE 52**
Decrease in the cost for integral bridge compared to non-integral bridges of different length.
**Source:** Author, 2024

**TABLE 21**
Estimated cost of 25m long non-integral bridge with 15m abutment height

| I. No. | Description of Works | Unit | Quantity | Unit Rate (USD) | Amount (USD) |
|---|---|---|---|---|---|
| 1 | Foundation investigations | PS | 1.00 | 13,333.3 | 13,333.3 |
| 2 | Clear the site and remove vegetation/trees | Ls | 1.00 | 6,666.7 | 6,666.7 |
| 3 | Excavation in soft materials and cart away | m3 | 828.00 | 6.7 | 5,520.0 |
| 4 | Excavation and cart away in hard materials | m3 | 1,242.00 | 16.7 | 20,700.0 |
| 5 | Back fill using hard materials/rock bottom fills | m3 | 1,012.50 | 20.0 | 20,250.0 |
| 6 | Back fill using imported selected materials top fills | m3 | 911.25 | 13.3 | 12,150.0 |
| 7 | Blinding Concrete C-15/20 | m3 | 103.50 | 106.7 | 11,040.0 |
| 8 | Class F2 Form work in Super Structure | m2 | 768.32 | 18.0 | 13,829.7 |
| 9 | Class F2 Form work in Sub Structure | m2 | 2,849.13 | 18.0 | 51,284.3 |
| 10 | High yield strength Fy=500MPa reinforcement steel in Super Structure | Tons | 33.90 | 1,833.3 | 62,157.9 |
| 11 | High yield strength Fy=500MPa reinforcement steel in Sub-Structure | Tons | 110.41 | 1,833.3 | 202,417.6 |
| 12 | Concrete C-35/45 in Super Structures | m3 | 230.48 | 198.7 | 45,788.1 |
| 13 | Concrete C-35/45 in Sub Structures | m3 | 1,226.59 | 192.0 | 235,505.3 |
| 14 | Elastomeric Bearing 500x500x70mm | Pcs | 8.00 | 1,166.7 | 9,333.3 |
| 15 | Concrete bridge railing using reinforced concrete crush barriers C-35/45 | m | 70.00 | 133.3 | 9,333.3 |

| I. No. | Description of Works | Unit | Quantity | Unit Rate (USD) | Amount (USD) |
|---|---|---|---|---|---|
| 16 | Expansion joint including 20mm filler | m | 22.00 | 166.7 | 3,666.7 |
| 17 | Expansion Joint Sealant | m | 22.00 | 33.3 | 733.3 |
| 18 | Rock fill in foundation | m3 | 600.00 | 20.0 | 12,000.0 |
| 19 | Weep Holes | Lm | 100.00 | 12.0 | 1,200.0 |
| 20 | Crushed stone in drainage strip | m3 | 60.00 | 26.7 | 1,600.0 |
| 21 | Water proof in deck and foundations | Ls | 1.00 | 8,000.0 | 8,000.0 |
| 22 | Design and supervision | Ls | 1.00 | 89,581.2 | 89,581.2 |
| 23 | Contingencies 5% | Ls | 1.00 | 40,804.5 | 40,804.5 |
| | Total cost in USD | | | | **876,895.3** |
| | Cost of the bridge per m length USD/m | | | | **35,075.8** |

**Source:** Author, 2024

**TABLE 22**
Estimated cost of 25m long integral bridge with 15m abutment height

| I. No. | Description of Works | Unit | Quantity | Unit Rate (USD) | Amount (USD) |
|---|---|---|---|---|---|
| 1 | Foundation investigations | PS | 1.00 | 13,333.3 | 13,333.3 |
| 2 | Clear the site and remove vegetation/trees | Ls | 1.00 | 6,666.7 | 6,666.7 |
| 3 | Excavation in soft materials and cart away | m3 | 645.8 | 6.7 | 4,305.6 |
| 4 | Excavation and cart away in hard materials | m3 | 968.8 | 16.7 | 16,146.0 |
| 5 | Back fill using hard materials/rock bottom fills | m3 | 911.3 | 20.0 | 18,225.0 |
| 6 | Back fill using imported selected materials top fills | m3 | 820.1 | 13.3 | 10,935.0 |
| 7 | Blinding Concrete C-15/20 | m3 | 69.0 | 106.7 | 7,360.0 |
| 8 | Class F2 Form work in Super Structure | m2 | 674.9 | 18.0 | 12,148.8 |
| 9 | Class F2 Form work in Sub Structure | m2 | 2,291.1 | 18.0 | 41,240.1 |
| 10 | High yield strength Fy=500MPa reinforcement steel in Super Structure | Tons | 30.6 | 1,833.3 | 56,180.5 |
| 11 | High yield strength Fy=500MPa reinforcement steel in Sub-Structure | Tons | 87.4 | 1,833.3 | 160,240.8 |
| 12 | Concrete C-35/45 in Super Structures | m3 | 202.7 | 198.7 | 40,266.7 |
| 13 | Concrete C-35/45 in Sub Structures | m3 | 962.5 | 192.0 | 184,798.6 |
| 14 | Elastomeric Bearing 500x500x70mm | Pcs | - | 1,166.7 | - |
| 15 | Concrete bridge railing using reinforced concrete crush barriers C-35/45 | m | 70.0 | 133.3 | 9,333.3 |
| 16 | Expansion joint including 20mm filler | m | - | - | - |
| 17 | Expansion Joint Sealant | m | - | - | - |
| 18 | Rock fill in foundation | m3 | 600.0 | 20.0 | 12,000.0 |
| 19 | Weep Holes | Lm | 100.0 | 12.0 | 1,200.0 |
| 20 | Crushed stone in drainage strip | m3 | 40.0 | 26.7 | 1,066.7 |
| 21 | Water proof in deck and foundations | Ls | 1.0 | 8,000.0 | 8,000.0 |
| 22 | Design and supervision | Ls | 1.0 | 72,413.7 | 72,413.7 |
| 23 | Contingencies 5% | Ls | 1.0 | 33,793.0 | 33,793.0 |
| | Total cost in USD | | | | **709,653.8** |
| | Cost of the bridge per m length USD/m | | | | **28,386.2** |

**Source:** Author, 2024

**TABLE 23**

Estimated cost of 25m long integral bridge and non-integral bridges with 15m abutment height

| I. No. | Length of the bridge [m] | Height of the Abutment [m] | Cost of Non-Integral bridge [USD] | Cost of Integral bridge [USD] | Cost saving/ decrease in cost [USD] | Percentage decrease in cost from non-integral to integral |
|---|---|---|---|---|---|---|
| 1 | 15.0 | 15 | 731,028.11 | 585,151.49 | 145,876.62 | 20.0 % |
| 2 | 20.0 | 15 | 827,970.45 | 667,832.45 | 160,138.00 | 19.3 % |
| 3 | 22.5 | 15 | 852,432.86 | 688,743.12 | 163,689.74 | 19.2 % |
| 4 | 25.0 | 15 | 876,895.28 | 709,653.78 | 167,241.49 | 19.1 % |

**Source:** Author, 2024

## CONCLUSION

Based on the experimental and analytical investigations, the following conclusions can be drawn:

Experimental results show that the increase of ultimate failure loads by 19.4% to 34.4% for integral bridge models as compared to non-integral bridges with the same reinforcement and sectional properties. The analytical computations supported by the experimental investigations reveals the decrease in cost by 19.1% to 20.0% for integral bridge as compared to non-integral bridges with the same length and height. Comparison ultimate loads at failure showed that the calculated value had good agreement with the test result, indicating the proposed empirical formulas and MIDAS CIVIL calculation method are reliable and accurate. Therefore, it can be applied to design integral bridges. From the above, the cost saving is significant for a developing country like Kenya with huge fiscal deficit, incorporating integral bridge design and construction in the infrastructure projects will relief the stress in project spendings, thus in the long run could reduce the deficit significantly (Macharia et al., 2022 and Macharia et al., 2023).

## RECOMMENDATIONS

The study recommends;

1. Incorporate integral bridge design and construction in the infrastructure projects in order to relief the stress in project spendings,thus reducing the deficit significantly.
2. That planners and engineers to adopt integral design and construction through a review of road design manual that dictate preference of integral design over non-integral concept.
3. That design and construction of integral bridges of up to 100m long in tropical climate like Kenya to save cost both in construction and maintenance.

It should be pointed out that the aforementioned conclusions are drawn based on limited test results. Therefore, more studies are needed to verify the repeatability of the test results and obtain conclusive evidences.

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