EUROCODE LOADS AND ITS IMPLICATIONS TO DESIGN OF BOX CULVERTS IN SRI LANKA

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Degree of Master of Science in Structural Engineering

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Declaration

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Abstract

The Box Culverts are drainage structures that allow to cross, small to medium scale water paths. They generally founded in soil where scouring is not an issue. The advantage of the box culvert is that it can be rested on the soil where low bearing pressures exists. Box culverts are also often used in expressway construction when underpasses are needed for the traffic of by-roads that crosses the expressway embankment. The present highway structure design practice in Sri Lanka is based on the British Standards of BS 5400 that was published by British Standard Institution (BSI) in 1978 and then amended a number of times subsequently and along with the Bridge Design Manual (1991), Published by Road Development Authority, the apex body of managing A & B class of road in Sri Lanka. Since the BS codes have been superseded by BS EN (the English version of Euro Codes) in March, 2010, it is now opportune to adopt the recommendations of BS EN for the structural design of highway structures and hence box culvert design will also need updating. In the research presented, a detailed study has been carried out as a comparative study by considering number of possible arrangements of Box Culverts that are typically used in Sri Lanka. The reason is that BS EN allows a loading regime from which different values can be selected in contrast to the current BS based practice. The detailed analysis, with finite element method (FEM) , have been carried out for different types of loading specified in the BS EN; the results have been compared with the resulting forces due to the currently adopted standards to find suitable loading levels that can be recommended for the adoption of Sri Lanka. The results are presented in graphical form to allow the selection of different levels of loading based on the effects on the main design parameters.

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1.0 Introduction

1.1 Background

Box culverts are widely used in roadways to cross small and intermediate water paths which meets along the roads. These are economical structures as it can be rested on a ground where bearing pressures are not great. If scouring of the ground is not an issue or engineering solution is possible for such an issue, these structures can be placed in water paths where low bearing pressures are existing. (AHEMED, 2006). Further, box structures are also used in expressway constructions as an underpasses where traffic of minor roads that crosses the expressway embankment.

The present design practice for highway structure in Sri Lanka is based on the British Standard, BS 5400 that was published by British Standard Institution (BSI) in 1978. The BS 5400 is a combined document of ten parts. It includes the guidelines for design and construction of steel, concrete, and composite bridges. (Clark, 1983) . Further Bridge Design Manual (1991) ,published by the Road Development Authority , is widely used for designs in Sri Lanka. The Road Development Authority is the state institution which acts as the apex body in managing A & B Class roads in Sri Lanka (RDA, 1991).

Since the BS codes had been superseded by BS EN (Eurocodes with National Annexures for United Kindom) in March 2010 (Denton, 2010) , there is an opportunity to adopt the recommendations of BS EN for the structural design of highway structures in Sri Lanka. Hence box culvert design will also need updating. In this research, a detailed study has been carried out by considering several possible arrangements of Box Culverts that are typically used in Sri Lanka. The reason is that BS EN allows a loading regime from which different values can be selected in contrast to the current BS based practice.

The detailed analysis, with finite element method (FEM), has been carried out for different types of loading specified in the BS EN; the results have been compared with the resulting forces due to the currently adopted standards to find suitable loading levels that can be recommended for the adoption in Sri Lanka. The results are presented in graphical form to allow the selection of different levels of loading based on the effects on the main design parameters.

1.2 The Objectives

- Identify the major differences between Eurocode and BS in respect to highway structure design and traffic loading.
- Establish the analysing models for various configurations of box structures. In this attempt , different Finite Element models are developed.
- Establish the critical traffic models for shorter span highway structures such as box culverts.
- Establish the appropriate values for parameters for Load Model 1 and Load Model 2 in context of Sri Lankan vehicular traffic.
- Partial fulfilment of required research study on preparation of National Annex for Eurocode traffic loads.
- Identify the future research requirement on this subject.
- Provide partial guidelines on traffic models in preparation of National Annex, Sri Lanka.

1.3 The Methodology

- A detailed literature survey is conducted to choose the standards/ specification to design of Box culverts in Sri Lanka.
- A detailed literature survey is conducted to choose the appropriate model for analysing and design of the box culverts.
- A detailed literature survey is conducted to decide the loading applicable to highway structures as per BS and Eurocodes.
- Finite Element models are developed to different spans, and loads are applied based on two standards.
- The structural responses for different configuration of structures are analysed and compared.
- The appropriate loading conditions are chosen, and recommendations are provided to prepare the National Annexure (NA) for Sri Lanka.

In this case, a comparative study between the two guidelines as well as the present Sri Lankan design practice is important. It will lead to realization of necessary adjustments to parameters that are specified by the NDP s in Eurocodes.

Throughout this study, the two-design code of practices, i.e., BS & Eurocode, are scrutinised, considering the actions applied on the box structures of various spans, the partial safety factors, the properties of materials and the structural effects .

The 3-dimentional Finite Element Models, using commercially available software, MIDAS CIVIL, are developed for various configurations of box structures. These models are loaded with different traffic loads/actions that specified by below code of practices.

1. Part 2: BS 5400: Specifications for Loads published in 1978.
2. Part 2: BS 5400: Specification for Loads published in 2006
3. BS EN 1991 -2-2003 : Eurocode 1 : Action on Structures : Traffic Loads in Bridges

The structural responses of the box structures for above load applications are identified and statistically compared. Then the structural elements are designed based on the relevant code of practices. In this regard, design spread sheets are developed in conjunction with BS and Eurocode concrete design guidelines. These spread sheets are developed to satisfy the Serviceability Limit State (SLS) and Ultimate Limit State (ULS) design criteria.

The ULS flexure design and shear designs are carried out conforming with Eurocode and BS concrete design guideline. In SLS, the crack widths are limited to comply with the requirements stipulated by the relevant code of practices.

This to compare the steel Reinforcement requirement relevant to the codes of practices. Further, this will explain how the difference in traffic loading of the two codes of practice will projected in Reinforcement design.

1.4 Significance of the Study

The roadway & highway structure designs in Sri Lanka, including box culverts & underpass box structures, are conducted in conjunction with the British Specifications of BS 5400 and the Bridge Design Manual (RDA, 1991). The Part 2 of the BS 5400 provides the specification for highway loadings (BSI, 2006). It has been initially published in 1978 and later, the document has been revised in 2006. In Sri Lanka, both versions of the part 2, BS 5400, are still in use (Chinthaka S.S.L.D, 2018).

Even the latest major bridge construction projects in Sri Lanka, such as the New Kelani Bridge project that involves construction of extra dose bridge over Kelani River and the Central Expressway Project, which consists with continuous post-tension Prestress Concrete (PSC) girders, have been adopted the BS 5400 (Gunawardena et al., 2015).

However, how long this practice can continue is a question as the updating of BS publications has been already ceased by BSI. In fact, the practice of BS codes that was conflicting with Eurocodes have been withdrawn from 31st March 2010, and since then, Eurocodes has become the main structural design standard in the UK (DMRB, 2016). In this scenario, the adoption of Eurocodes is essential and inevitable for Sri Lanka.

However, this is not possible without due consideration of the traffic loads and existing design practice in Sri Lanka. Furthermore, the adaptation of the Eurocode guidelines should not cause excessive cost escalations in structures without sound reasons (Seyanthan and Jayasinghe, 2013).

The Eurocodes (EC) allow the selection of various design parameters based on a country-specific data, and these are broadly categorized as Nationally Determined Parameters (NDPs) (Denton, 2010; Bouassida, et al., 2012). The country which adopts Eurocode is required to publish its' recommended values for NDPs in their National Annex (NA). For example, the traffic load cases, Load Model 1 & 2 in Eurocode are included with adjustment parameters α and β and their default values are given as 1. This is corresponding to the most severe case of traffic loads, and NA is expected to provide the appropriate country-specific values (Eurocode, 1991).

The Sri Lanka Standards Institute (SLSI) is the authorised regulatory body to prepare the National Annexure, which is essential in practising Eurocodes in Sri Lanka (SLSI, 2016). In this regard, SLSI has formed a working group for preparation the National Annexures for Eurocodes. Also, as the apex Engineering body in Sri Lanka, the Institution of Engineers, Sri Lanka (IESL) has entered into a Memorandum of Understating with SLSI to provide expertise and financial assistance to this working group, in view of preparing National Annexure (President(IESL), 2013). From 2005, the standards published by British Standard Institution (The BS Codes) are obsolete, and the construction industry of Sri Lanka and relevant authorities must speed up preparing the National Annexures for proper lawful engineering practice to sustain.

A study conducted by Seyanathan and Jayasinghe, 2013, for bridge decks using Y- beams and M -beams, considering BS 5400 (2)-1978 loadings for the comparison, has recommended adopting 70% of the traffic loads of Eurocode for class B, C, D roads in Sri Lanka. The same study recommends the adoption of 85% of traffic loads in Eurocode for class - A roads (Seyanthan and Jayasinghe, 2013).

The above study is conducted for medium spans of 10m to 31m, whereas this study is conducted for box culverts covering the span range of 1m to 8 m. The Eurocodes, in conjunction with EN 1991-2, the traffic loads on bridges, introduces the Load Model 2 (LM2), which is expected to be prominent for shorter spans. Thus, the effect of LM 2, which identified as a Nationally Determined Parameter (NDP), β, which is to be defined in NA is studied extensively in this study.

The structural response of the box culverts is greatly affected by the actions other than the traffic actions, such as earth pressures, surcharges, and temperatures. This brings the combinations of actions into the picture. When combinations of loads or actions are concerned, the Eurocode practice is vastly different from the current BS practice. The combination of actions in Eurocode is complex, where all temporary actions are to be considered, simultaneously, along with leading variable action other than the exclusions provided in the Annex A2 of EN 1990: Application of Bridges (Normative), which provide supplementary rules for combinations of actions in highways.

This study is conducted to examine the above issues in the Sri Lankan design context and to make necessary recommendations for the future NA of Sri Lanka.

With increased road traffic and rehabilitating of the roads, whether to reconstruct or rehabilitate the existing structure is an important decision to be made (Chandrasiri and Jayasinghe, 2001). In the case of rehabilitation of existing box culverts, it is important to assess the strength of the structure in relation to present-day bridge design practice. In future, when Euro codes are adopted, this assessment should be on a reasonable basis, and this study facilitates the assessor to arrive at the decisions reasonably.

Furthermore, in structure rehabilitation, the widening of the existing box culvert is taken place often. However, in this case, the strength of the structure, explicitly in the box culvert, must be evaluated with the increased dead and live loads. Since these existing culverts are designed as per previous BS guidelines, it is important to assess the structural integrity of the existing structure (Chandrasiri and Jayasinghe, 2001). With the introduction of Eurocode in future, it is important to assess the existing structure for new guidelines explicitly when widening is taking place. However, Design Manual for Road & Bridges (DMRB) (BD 100/16), an explicit guideline on using Eurocode to design highway structures in United Kindom, is not recommending the Eurocode to assess highway structures that were not designed to Eurocode (DMRB, 2016).

As previously described , the study by Seyanathan and Jayasinghe (2013) has proposed a modified regime of traffic loading for the Eurocode to adopt in Sri Lanka . This type of adjustment based on the traffic level relevant to each country is possible because Eurocodes provide room to develop National Annexures (NA) that contains the information on parameters which are left open by Eurocodes for national choices (Denton, 2010). The output of this research study will validate the above conclusions, appropriately , for smaller span and box culverts.

The EN 1991-2, the traffic loads on bridges, specifies a load case, Load Model 2 (LM2), that prominent in short spans in the range of 3m to 7m. The previous study on adoption of Eurocodes in Sri Lanka by Seyanthan & Jayasinghe 2013 is conducted for medium spans of 18m to 28m. Since this study is conducted for box culverts that cover the span range of 1m to 7m , the effect of LM 2 is studied extensively. Further, as previously elaborated, this load case is defined as a Nationally Determined Parameter (NDP), β, which needs to be defined in NA. The LM 2 is a single axel load and its contact tyre area is different from Load Model 1 (LM1). However, EC suggests adopting the same square contact surface for LM 1 & LM 2 for simplicity vide NA (Note 2, cl 4.3.3, EN 1991-2). This study is conducted to examine these issues in the Sri Lankan design context and to make necessary recommendations for future NA of Sri Lanka.

Since design and analysis procedures set out by Eurocode are based on the first principles, they can be used to assess the existing structures(Hendy et al.).

This study will extensively find the available methods of analysis owing to applied loads on box culvert and their structural effects.

1.5 Outline of the Research

First chapter of the thesis provides a description of the research question. It presents a brief description of the box structures used in SL and the design practices adopted. With the obsolete BS codes, it is vital to adopt Eurocode in the design of highway structures. In this background, research methodology is developed to identify the requirements in Eurocode and how far does Eurocode harmonise with the present highway structure design practice of SL.

The literature review of the study, provided in section 2, includes the basic introduction to the box structures. Then it continues to examine the basic concepts behind Eurocode traffic loads and how it incorporates in the structural analysis and the design. In the latter part, it examines how various load effects are incorporated to design in conjunction with Eurocode . During this discussion, it continues to compare how two codes of practices differ from each other in relevant aspects such as design and analysis of loads. Lastly, a detailed literature review has been carried out to determine how United Kingdom has adopted the Eurocode in their highway structure design. This is significant because historically, Sri Lankan practice of highway structure design is closely related to the past UK practice.

Chapter 3 is providing a detailed evaluation of the Eurocode and BS traffic loads and how these loads incorporate into the different configurations of box culverts considered. Then it continues with the details of structural idealisation in FE model. Later a case study has been conducted to evaluate how these aspects are incorporated into a 3x3 box structure.

Chapter 4 deals with the outcome of the analysis described in chapter 3. It examines how different traffic load models in Eurocode provide critical structural effects in different configurations of box structures. A similar procedure is carried out corresponding to the BS load specifications as well. Then it proceeds to compare the structural effects owing to actions of two code of practices. Finally, a comparison has been carried out with reduced Eurocode loads to establish the amount of reduction required to harmonise with effects that BS loads provide.

Chapter 5 is about concrete design with BS and Eurocode . The SLS and ULS design criteria of both codes of practices are scrutinised and detailed design has been conducted for mid-span of the top slab in different configurations of the box culverts. An attempt has been made to compare the amount of Reinforcement required and compare them.

In chapter 6, conclusions are postulated based on the outcome of chapter 4 and 5. Further, it provides recommendations in adopting Eurocode in Sri Lanka for highway structure design.

2.0 Literature Review

2.1 Box Culvert

In general, the box culvert structures have a single deck and a foundations where these act as horizontal slabs. These slabs are rested on minimum of two vertical walls. When number of vertical walls are exceeded two, it constitutes several openings for water flow and termed as multi cell box culverts. The box culverts can be found in road, railway, or irrigational systems. For smaller waterways with high embankments, box culverts are ideal solution.(Kim and ChaiH.Yoo, 2002). Often, the culverts are considered as economical than the bridges where the opening of the discharge is less than 15m^2 and high embankment exists (Ahmed and Alarabi, 2011).

2.1.1 Material uses.

There are a wide range of culverts in practice worldwide and broadly categorised into two types, such as, rigid and flexible. The differences between these two are owing to the mechanism that transfers the loads in to the surrounding soil. In rigid types, the transfer occurs by bending of the components. Generally, the rigid types are made of concrete. The flexible are made of steel (Ahmed and Alarabi). This research study is limited to box culverts made of concrete as shown in Figure 1, and therefore it is limited to the rigid types.

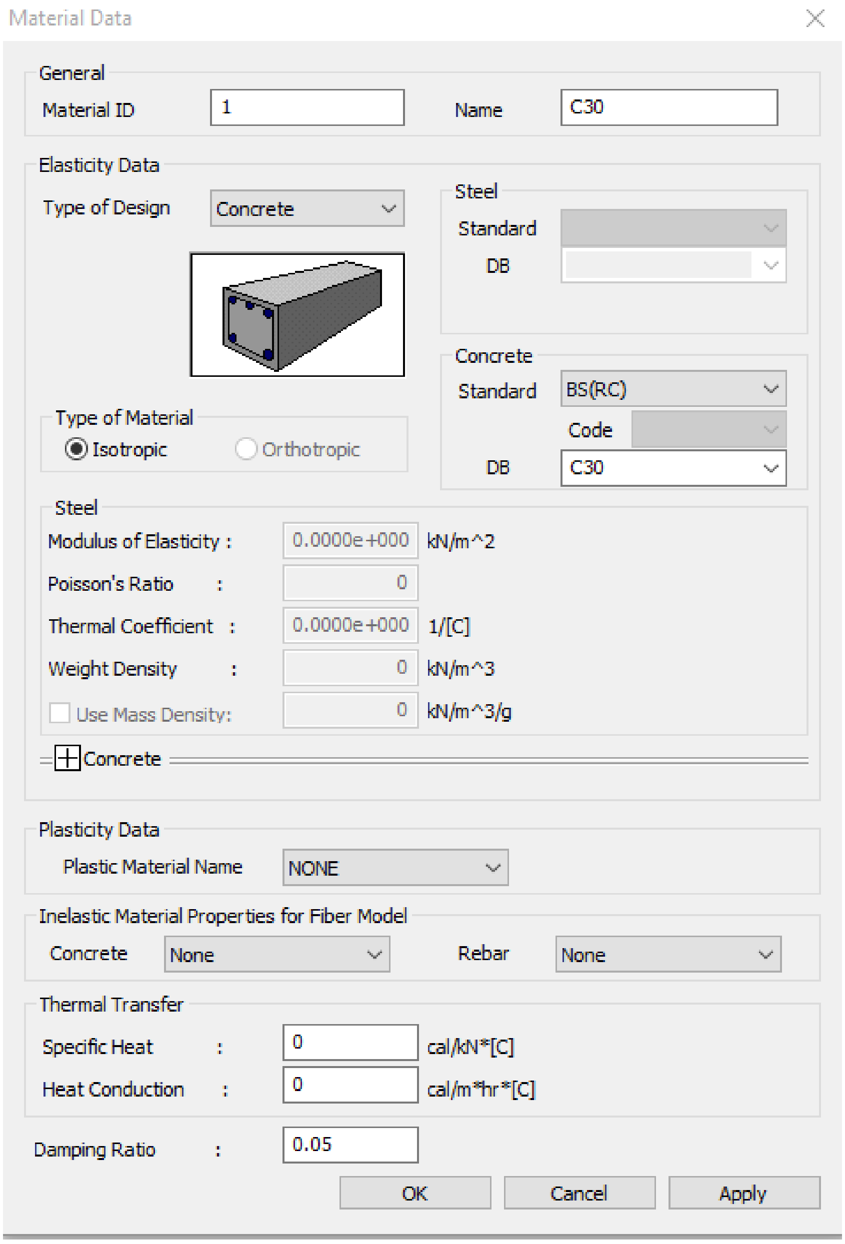


Figure 1 : Material Selection for FEM, Midas Civil

In this study, similar grade of concrete is selected for both code of practices of BS and Eurocodes. The Grade of Concrete with Characteristic Cylindrical Strength of (f_{ck}) 25 MPa is selected where its Characteristic Cube Strength is 30 MPa. The selection of concrete strength is in line with widely used present day practice in Sri Lanka.

2.1.2 Construction practice

The pre cast segmental construction and the cast in situ construction are two different but widely used construction methods for box culverts (Ahmed and Alarabi, 2011). It is essential to identify the common practice in Sri Lanka to identify the appropriate analysis and design methodology.

The cast in situ or precast reinforced concrete box structures are widely used by many highway authorities thorough out the world. Though construction of small pre cast box culverts in the range of 1x1 m to 3mx3m are gaining recognition in Sri Lanka, recently, the cast in situ method is the most common practice in Sri Lanka. However, the author has designed large precast box culverts (5.5m x 6m) for the Toppuwa- Dankotuwa- Nathtandiya- Madampe (TDNM) road project in to an explicit request from a client. However, these instances are not regularly met owing to formwork, handling, transportation and installation difficulties which may be challenging for Sri Lankan construction industry .

2.1.3 Design Practice

The present design practice in Sri Lanka for box culvert mainly based on the old British Standards of BS 5400. The Part 2 of BS 5400, which provided the guidelines for highway live loadings, has two editions. i.e

1. BS 5400 -2 :1978 – Specification for Loads , Steel, Concrete and Composite Bridges
2. BS 5400 -2 :2006 – Specification for Loads , Steel, Concrete and Composite Bridges

In Sri Lanka, both these code of practices are still in use (Chinthaka S.S.L.D, 2018).

In addition to above, the Bridge Design Manual published by the Road Development Authority of Sri Lanka provides a general country specific guidelines for highway structure design (RDA, 1991).

Further, explicit guidelines for design of box structures are not provided in above publications as these are dealing with general bridge design issues. Owing to lack of structure specific guidelines for box culverts, many road structural designers in Sri Lanka have opted for the UK practice where Design Manual of Road and Bridges (DMRB) has provided a tailor-made guideline for box culverts vide article BD 31/01 (DMRB, 2001)

2.2 Eurocode Loading

2.2.1 background to Eurocode

The initial preparation work for Eurocode were first appeared in early 70's where steering committee was formed to identify and build, a common set of code of practices for construction industry in the European countries. It was tasked with identifying the differences of various practices by members of European countries and then making a common platform to work on. The initial draft start to appeared in 1976 to 1990 (Bond & Harris, 2008). Initial drafts were termed as Provisional European Standards which acronym as ENVs. These were published by the European Committed for Standardisation which and acronym as CEN. The ENVs were converted into Eurocodes between 1998 to 2006 (Bond & Harris, 2008).

Now Eurocode stand as an absolute document. It is also regarded as a state of the art, code of practice as it was built, based on the latest research findings. (Denton, 2010).

The Eurocode has complied in a unique way where it has characterized its clauses either into Principles or Rules of Applications. Principles are acronym as 'P' and fundamental argument has been described under letter 'P'. (Bond & Harris, 2008). The Rules of Applications in Eurocode are integrating with the Principles given in the Eurocode (Monteverde, 2017) .

Eurocodes include many guidelines for different aspects of design (BSI, 2004). The outline below, is a descriptive of each of these different Eurocodes

- BS EN 1990 Basis of Design
- BS EN 1991 Action on Structures (Eurocode 1)
- BS EN 1992 Design of Concrete structures (Eurocode 2)
- BS EN 1992 Design of Concrete Structures (Eurocode 3)
- BS EN 1993 Design of Steel Structures (Eurocode 3)
- BS EN 1994 Design of Composite Steel and Concrete Structures (Eurocode 4)
- BS EN 1995 Design of Timber Structures (Eurocode 5)
- BS EN 1996 Design of Masonry Structures (Eurocode 6)
- BS EN 1997 Geotechnical Design (Eurocode 7)
- BS EN 1998 Design of Structures for earthquake Resistance (Eurocode 8)
- BS EN 1999 Design of Aluminium Structures (Eurocode 9)

Among these guidelines, the load specifications for bridges are given in BS EN 1991 – Action on Structures.

The following Eurocodes, given by Figure 2 , are superseding the previous British Codes, BS 5400, for the design of concrete and steel bridges.

Eurocode	Superseded British Standards
EN 1991 -1-1	BS 6399 -1 :1996
EN 1991 -1-2	None
EN 1991 -1-3	BS 6399 -1 :1996
EN 1991 -1-4	BS 6399 -1 :1996, BS 5400-2
EN 1991 -1-5	BS 5400-2
EN 1991 -1-6	None
EN 1991 -1-7	None
EN 1991 -2	BS 5400-1, BS 5400-2
EN 1991 -3	None
EN 1991 -4	None

Figure 2 : Superseded BS standards by Eurocodes (BSI, 2004)

In conjunction with the above summary, the loads covered by the part 2 of BS 5400 are partly replaced by the following set of Eurocodes, and the relevant code covers the specific load cases stated as below.

1. For Wind related Load evaluations, the Part 2 of BS 5400 is replaced by EN 1991-1-4 Wind Actions
2. For Temperature induced loads, including mean and differential temperature gradient part 2 of BS 5400 is replaced by EN-1991 – 1 -5
3. For vehicle and pedestrian loads Part 2 of BE 5400 is replaced by EN 1991-2 – traffic loads on Bridges and Annex 2 of BS EN 1990:2002

2.2.2. Major concepts in Eurocode loadings

Six key concepts, conjunction to bridge design in the context of Eurocode have been identified (Bouassida, et al., 2012).

1. Design Situation - Design should accounted for all situations that sufficiently severe and varied actions during its intended life span. All the actions are classified into Persistent, Transient, Accidental and Seismic design situations (Bouassida, et al., 2012).

   Persistent actions are described as the loads that structure will meet during its normal operations. The temporary loads which structure will meet, in respective to its design life is identified as Transient actions. The major difference between the Persistent and Transient is that the duration of the exposures to those actions (Bond & Harris, 2008; Denton, 2010). In highway structures, since the structure is exposed to traffic load during its normal use, the traffic load is considered as Persistent design situation (Bouassida, et al., 2012).

   Accidental design situation refers to rarely occurring accidental situations and, importantly, some degree of damage to the structure is allowed.

   Seismic design situation refers to actions which structure must bear during the seismic events.

2. Reversible and Irreversible Serviceability Limit State (SLS) (Bouassida, et al., 2012)

   Not all the SLS combinations are of equal importance, where irreversible combinations are more onerous.

   For example, a beam under UDL may deflect, and once the load is removed, the beam comes to its original shape, provided that the beam is in the elastic range. However, should stress limits of the steel (which also is an SLS design criterion) do increase, the damage is much severe than the deflection criteria. Therefore, EC introduces two different SLS criteria, i.e reversible and irreversible, so that adequate concerns can be given in conjunction with the severity of the SLS. This approach is different from the previous BS practice, where explicit attention was not paid based on the reversible or irreversible state in SLS.

This has the minor effect for design of highway structures. However, it is important to understand the different SLS combinations defined by Eurocode.

3. Representative values of Variable Actions (Bouassida, et al., 2012).

In Eurocode, the actions are grouped as per their duration of exposure to the structure, i.e.

Permeant Actions (G) – self-weight of the structure, surfacing of the road, differential settlement

Variable Action (Q) – traffic load, temperature, wind

Accidental Action (A) – impact from vehicles

Four different representative values are defined for variable actions. The characteristic value is the major representative value. Other representative values, i.e. combination value, frequent value & quasi permanent value, are denoted by ψ_0,ψ_1,ψ_2 respectively, These are less extreme, statistically, and always less than 1. The Figure 3 graphically shows the relationship of above four representing values.

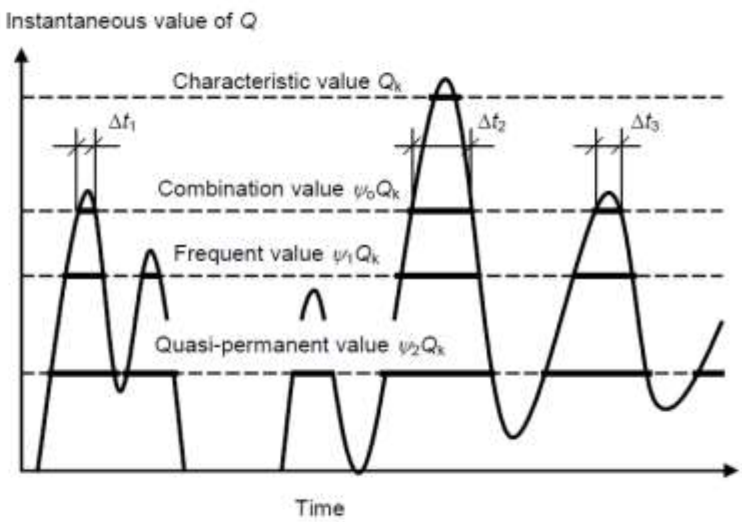


Figure 3 : Four representative values of the variable actions (Bouassida, et al., 2012)

4. Six Ultimate Limit States (ULS)

   The Eurocode identifies the six Ultimate Limit State (ULS) designs in various aspects. These ULS including Equilibrium (EQU), Structural (STR) , Geotechnical (GE)), Fatigue (FAT) , Uplift (UPL) and Hydraulic Heave (HYD) .

   Among these EQU, UPL and HYD is mainly related to analysis and evaluation on structure stability. The UPL and HYD is more related to uplift and seepage issues relevant to irrigational structures. The STR, GEO and FAT are corresponding to the resistance provided by structural , geotechnical and fatigue induced actions.

5. Single Source Principle.

   When it comes to the response of a structure, some actions which originated from same source may be favourable or unfavourable, simultaneously. For an example in an abutment wall, higher retain mass will create higher bending moments for walls. Therefore high retain mass is unfavourable. However high retain mass of soil will be favourable for resistance provided against the structural overturning.

   In these instances, Eurocode specifies to adopt single partial safety factor. appropriately. (Bouassida, et al., 2012). This principle is applied for safety factors used in ULS for STR & GEO. However, this principle is not applied in ULS for EQU, where the stability of the structure is considered.

6. Combinations of the actions

Unlike in BS 5400-2, where different load combinations are considered for different loads such as wind and temperature, the Eurocode specify to consider all the possible actions simultaneously.

When combining the characteristic loads, the factors are distinguished for three categories for permeant ,leading variable and accompany variable actions. These actions are added by applying specific combine factors. Later another factor of safety, greater than 1, is added to obtain design actions. This procedure is graphically shown in Figure 4.

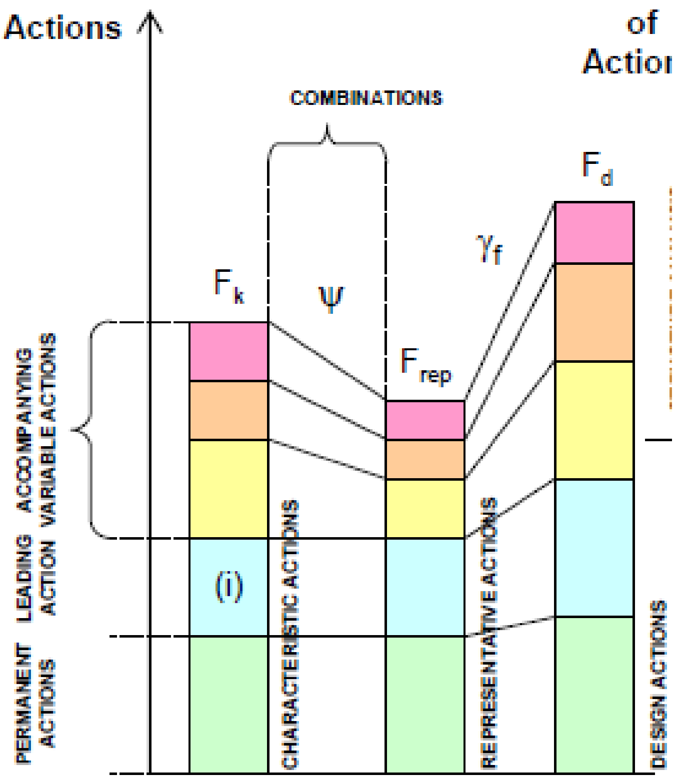


Figure 4 : Combination of Actions in Eurocode (Bouassida, et al., 2012)

In bridge design, the traffic loads are further simplified by grouping them to load groups

In Eurocode , for Ultimate Limit State (ULS) verifications, three combinations are recommended base on the respective design situation. For persistence & transient design situation, the most general case, only permanent actions, prestress, and variable actions are considered overlooking accidental and seismic loads.

For ULS , Accidental design situations all permanent, prestress, variable and accidental loads are considered but incorporating the reduced safety factor for variable actions. The rationale behind this concept lies that there is a low probability for occurring all the variable actions and accidental actions, with their characteristic values, at a single instance in the design life period of a structure.

For ULS, seismic design situation , all the permeant , prestress, variable , accidental and seismic loads are incorporated. Again, reduced safety factors are incorporated for variable actions owing to reasons described above.

For Serviceability Limit State (SLS), Eurocode specified three combinations of actions. Those are identified as 1. Characteristic Combinations 2. Frequent Combinations and 3. Quasi Permanent (Bouassida, et al., 2012)

For irreversible effects on structure the characteristic combinations of SLS are recommended. For reversible effects, such as deflections, the Frequent combinations can be incorporated. For long term creep induced structural effects can be verified with Quasi Permanent combinations.

The Table 1 summarises the different load combinations described in Eurocode.

Table 1 : Combinations of Actions in Eurocode

Ultimate Limit State (ULS)	1. Persistent and Transience combination 2. Accidental Combination 3. Seismic Combination
Serviceability Limit state (SLS)	1. Characteristic Combinations (for irreversible effects) 2. Frequent Combinations (for reversible effects) 3. Quasi Permeant combination (for long term creep)

2.2.3 The significant differences between code of practices

The major differences between the two codes of practices are about load configurations, load intensities, the division of notional lanes and application of partial safety factors. These are discussed in detail in below.

1. Interpretation of Notional Lanes

   In BS 5400 the number of notional lanes are defined base on the width of the carriageway where resulting width of a notional lane would be varying from 2.5m to 3.65m approximately .

   In contrast, the Eurocode defines the width of notional lanes as a constant of 3m wide as all carriageways except for 5.4m to 6m as shown in Figure 5. In these range, the Eurocode defined the width of Notional Lane as the half of the width of carriageway (Atkins, 2004)

The lane width of 3m is much closer to the vehicle distribution in an actual situation. If higher lane widths are considered then the bunching effect should be accounted. The bunching effect is described as three vehicles loaded side by side in a two-lane width (Atkins, 2004).

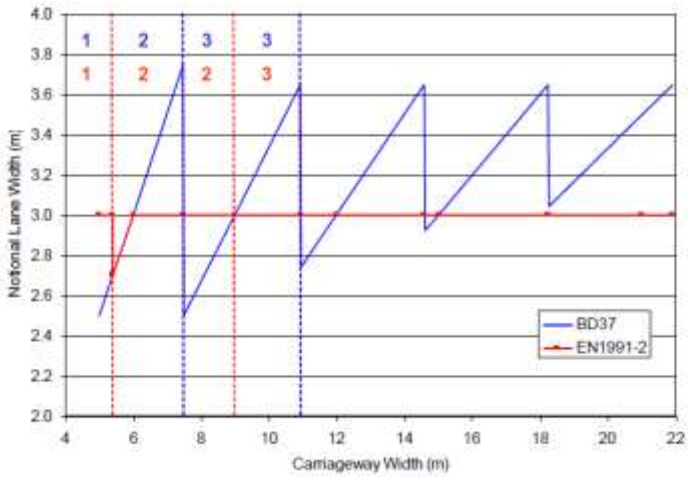


Figure 5 : Comparison of Lane Width and Number of Lanes between BS & EC (Atkins, 2004)

2. Load Intensities

In comparing the LM 1 of Eurocode & HA of BS 5400, the critical structural effects of HA are owing to Uniformly Distributed Load (UDL) , while in LM1, it occurs owing to tandem axle system up to 40m (Atkins, 2004).

In conjunction with   part 2 of BS 5400(2006) the HA UDL has a steep decline when loaded length increased up to 40. For loaded lengths that greater than 40m , the HA UDL is not greatly reduced and evaluated by 36 $(1/L)^{0.1}$ (BSI, 2006). This phenomena is depicted by Figure 6 where it has been extracted from Part 2- BS 5400 (2006)

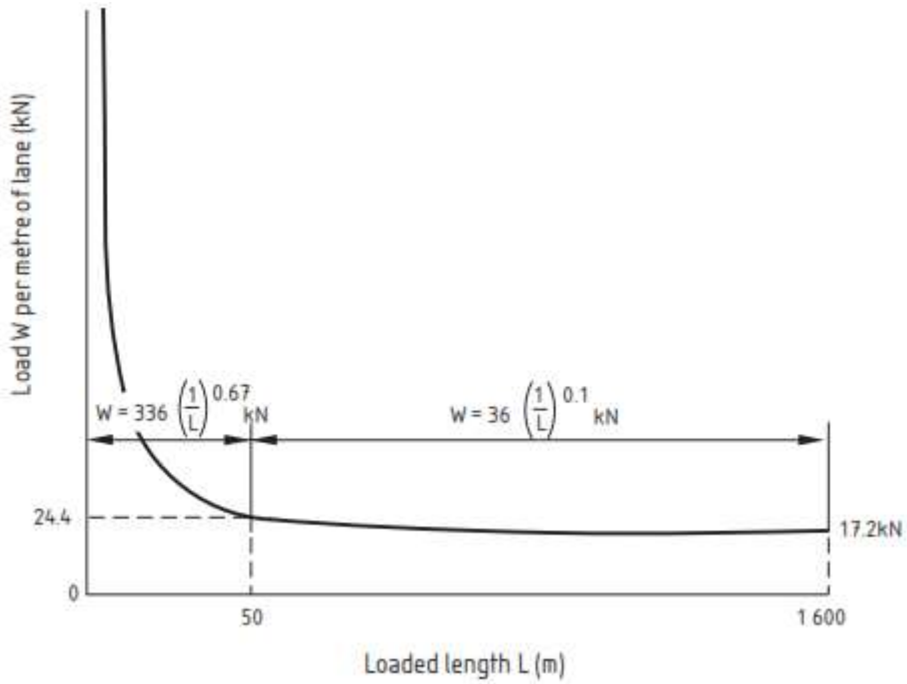


Figure 6 : UDL of the HA is rapidly drop up to 40m (BSI, 2006)

However, in LM1 in Eurocode, the relevant traffic case for HA, the load intensity of UDL and tandem system remains constant for all loaded lengths (BSI, 2004).

3. Lane Distribution of Loading.

There exists a reduced probability that all the notional loads are loaded with the maximum traffic loads. This phenomenon is well addressed in both code of practices.

In part 2 of BS 5400 (2006) , the first two notional lanes have a lane distribution factor of 1 and in third lane, it reduced to 0.67. The Figure 7 is providing the distribution factors for each notional lanes in detail for HA UDL in conjunction with BS 5400 (2006)

Loaded length L m	First lane factor β_1	Second lane factor β_2	Third lane factor β_3	Fourth and subsequent lane factor β_n
$0 < L \leq 20$	α_1	α_1	0.6	$0.6\alpha_1$
$20 < L \leq 40$	α_2	α_2	0.6	$0.6\alpha_2$
$40 < L \leq 50$	1.0	1.0	0.6	0.6
$50 < L \leq 112$ $N < 6$	1.0	$7.1/\sqrt{L}$	0.6	0.6
$50 < L \leq 112$ $N \geq 6$	1.0	1.0	0.6	0.6
$L > 112$ $N < 6$	1.0	0.67	0.6	0.6
$L > 112$ $N \geq 6$	1.0	1.0	0.6	0.6

NOTE 1 $\alpha_1 = 0.274b_L$ and cannot exceed 1.0

$\alpha_2 = 0.0137\{b_L(40 - L) + 3.65(L - 20)\}$

where b_L is the notional lane width (m)

NOTE 2 N

shall be used to determine which set of HA lane factors is to be applied for loaded lengths in excess of 50 m. The value of N shall be taken as the total number of notional lanes on the bridge (this shall include all the lanes for dual carriageway roads) except that for a bridge carrying one-way traffic only, the value of N shall be taken as twice the number of notional lanes on the bridge.

Figure 7 : Lane distribution factors for HA UDL given in part 2 : BS 5400 (2006) (BSI, 2006, p. 48)

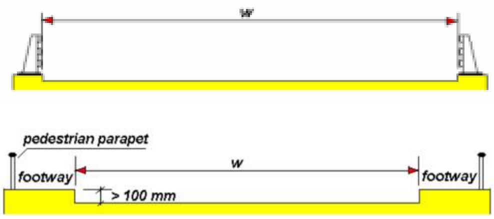
As earlier explained, in LM1 of Eurocode, the Tandem loads govern over the UDL values (Atkins, 2004). For LM1 , the Tandem load on lane 2 is two third of the the 1st lane. In lane 3 it is one third of first lane.

4. Partial Safety Factors

In BS 5400, the load partial factors for traffic live load are $\Upsilon_{fL} = 1.5$ and $\Upsilon_{f3} = 1.1$, amounting overall factor of 1.65 for ultimate limit state while in Eurocode $\Upsilon_{fL} = 1.35$.

The Table 2 summarises the major differences and similarities between two code of practices i.e BS 5400 and Eurocode

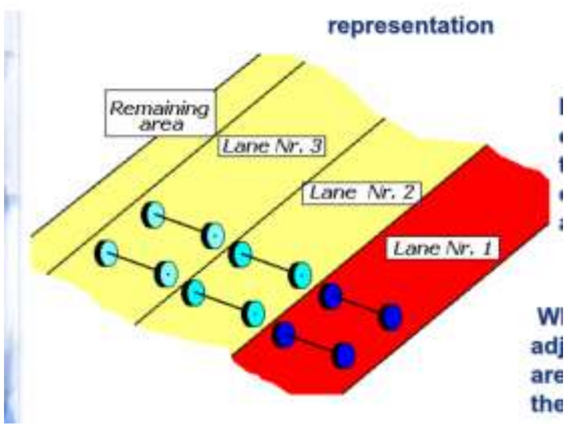
Table 2 : Summary of Major Differences Between BS and Eurocode

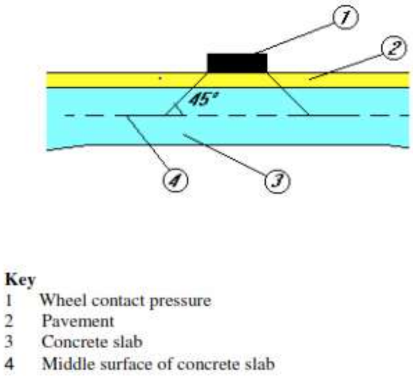
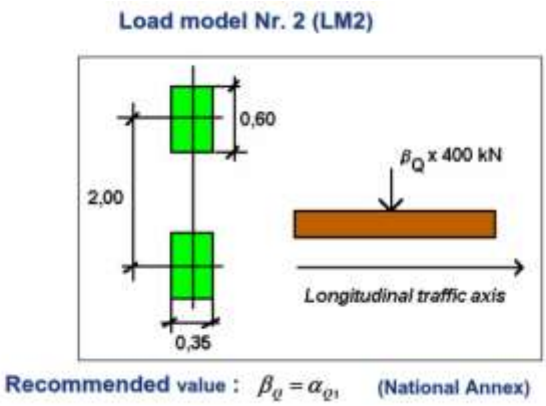
<table>
<tr><th>BS 5400 and Bridge Design Manual (RDA) Guidelines</th><th>Eurocodes Guidelines</th></tr>
<tr><td colspan="2">1.0 Codes</td></tr>
<tr><td>BS 5400 part 2 (1978)
BS 5400 Part 2 (2006)
The Design of Buried Concrete Box and Portal Frame Structures. BD 31/01</td><td>EN 1991 –2 – Traffic Loads on Bridges
EN 1991-1-4 : Wind Actions
EN 1991 – 1- 5 Thermal Effects
Anne A2 to BS EN 1990 :2002 – Rules and methods for establishing the combination of Actions (Load Combinations) for ULS and SLS</td></tr>
<tr><td colspan="2">2.0 Geometrical</td></tr>
<tr><td>The width of the carriageway given as the distance between kerbs</td><td>The width of the carriageway taken as the distance between kerbs


(Calgaro, 2008)
Minimum Kerb Height is 100mm and it is a NDP (BSI, 2003).</td></tr>
<tr><td>In view of applying the load, the carriageway is divided into notional lanes.
3.2.9.3.1
carriageway widths of 4.6 m or more
notional lanes shall be taken to be not less than 2.3 m nor more tha
divided into the least possible integral number of notional lanes ha
<table>
<tr><th>carriageway width m</th><th>number of notional lanes</th></tr>
<tr><td>4.6 up to and including 7.6</td><td>2</td></tr>
<tr><td>above 7.6 up to and including 11.4</td><td>3</td></tr>
<tr><td>above 11.4 up to and including 15.2</td><td>4</td></tr>
<tr><td>above 15.2 up to and including 19.0</td><td>5</td></tr>
<tr><td>above 19.0 up to and including 22.8</td><td>6</td></tr>
</table>

(BSI, 2006)</td><td>The loads are applied to Notional lanes and this concept is in line with the BS practice. However, the calculation of the number of notional lanes is complex comparatively.
<table>
<tr><th>Carriageway width w</th><th>Number of notional lanes</th><th>Width of a notional lane w_l</th><th>Width of the remaining area</th></tr>
<tr><td>$w < 5,4\,m$</td><td>$n_l = 1$</td><td>3 m</td><td>$w - 3m$</td></tr>
<tr><td>$5,4m \leq w < 6m$</td><td>$n_l = 2$</td><td>$\frac{w}{2}$</td><td>0</td></tr>
<tr><td>$6m \leq w$</td><td>$n_l = Int\left(\frac{w}{3}\right)$</td><td>3 m</td><td>$w - 3 \times n_l$</td></tr>
<tr><td colspan="4">NOTE For example, for a carriageway width equal to 11m, $n_l = Int\left(\frac{w}{3}\right) = 3$, and the width of the remaining area is 11 - 3x3 = 2m.</td></tr>
</table>

(BSI, 2003)</td></tr>
</table>

3.0 Traffic Loads	
Traffic Load Models : Vertical	
Represented by HA, HB, and Pedestrian Loads	Represented by Load Models LM1, LM2, LM3 & LM4
HA traffic Load simulated the general traffic load met by roadway structure. It has two components. One is uniformly distributed load (UDL) and secondly knife edge loads (KEL) (BSI, 2006)	Load Model 1 (LM1) represent the general type traffic load in a roadway. It has two components such as uniformly distributed load (UDL) and axel loads . Axel loads is named as Tandem system (TS) (BSI, 2004).  (Bouassida, et al., 2012; Calgaro, 2008) Includes an adjustment factor α. When α=1 , it corresponds to heavy industrial international traffic. For common traffic composition, a moderate reduction of α, 10% to 20% can be adopted via National Annexure.
Abnormal Types of Vehicle Loads are represented by HB loading that consists of 4 axles. Each axle consists of 4 wheels.	Relevant traffic model for represent special type of vehicle is Load Model 3. This is included with many axel loads. This is a Nationally Determined Parameter (NDP) and should include in the National Annex (NA)

Pedestrian load is defined. Up to loaded length of 36m, the pedestrian loads is defined as 5 kN/m²	Relevant load case to simulate the crowd and pedestrian load in Load Model 4. This is uniformly distributed load of 5 kN/m²
Dispersal of concentrated loads (HA single wheel and HB single wheel) through the deck and pavement is defined as 1 horizontally to 2 vertically.	Dispersal of tandem system loads through the deck and pavements is 1 to 1. Dispersal of Concentrated Loads are included  (BSI, 2004)
No relevant traffic load is defined to compare with LM 2	Load Model 2 (LM2) is defined as a single axel load . It has a nationally define parameter (NDP) of β_Q  (Calgaro, 2008)

Traffic Load Models: Horizontal	
Traction, centrifugal, accidental skidding, collision loads on bridge parapets and supports are defined.	Traction/ Centrifugal are both included
Traction forces The maximum force is limited to 750 kN and applied in a single lane, Traction = 8x Span +250 < 750 kN	Braking and Acceleration force : Maximum is limited to 900 kN Applied to Lane No 1 $Q_{lk} = 0,6\alpha_{Q1}(2Q_{1k}) + 0,10\alpha_{q1}q_{1k}w_1L$ $180\alpha_{Q1}\,(kN) \leq Q_{lk} \leq 900\,(kN)$ (BSI, 2004) For 3m wide lane Traction == 2.7 x span +360 <900 kN
5. Load Combinations	
Five major load combinations are defined. Combination 1 – All permanent loads are accounted together with vertical live loads. The wind & temperature loads are neglected. Combination 2 - All permanent loads are accounted together with vertical live loads. The wind loads are accounted but not temperature. Combination 3 - All permanent loads are accounted together with vertical live loads. The Temperature loads are accounted but not wind. Combination 4 - All permanent loads are accounted together with vertical and horizontal live loads. The temperature & wind loads are not accounted.	All permeant and variable actions are considered simultaneously. However, exceptions are introduced vide the Annex A2 of EN 1990: Application of Bridges (Normative), provide supplementary rules for load combinations. Accordingly, the snow and wind loads are not required to combine with 1. horizontal loads such as braking, acceleration or centrifugal forces. 2. load on footways and cycle tracks 3. crowd loading (CEN, 2005) Further, in conjunction with cl. A2.2.2(2), Annex A2- BS EN 1990, LM 2 and associated Load Group gr1b (Load Model 2) is not required to combine with other variable load actions except for traffic induced loads (CEN, 2005).

Combination 5 - All permanent loads are accounted together with temperature loads for bearing.	Additionally, Wind action and Thermal Actions need not to consider simultaneously (CEN, 2005).

2.3 The Design Method

2.3.1 Construction stages to be analysed

BD 31/01, DMRB specify three stages of box culvert to be analysed.

- The completed structure that is backfilled up to its slab top level
- The completed structure with an intermediate level of earth fill where construction loads are applicable in approaches.
- The completed structure with full earth fill while the structure in service (DMRB, 2001).

Since no earth fill is considered in this study, only the 3rd stage, the completed structure in service, is considered in this analysis.

2.3.2 Fatigue

Eurocode provides a specific system of traffic loads to evaluate the fatigue of highway structures.

However, cl 6.8. of BS EN 1992-2:2005, Concrete Bridges-Design and Detailing Rules provides explicit guidelines on the instances where fatigue should be accounted. The verification of fatigue is required only if structure component is subjected to regular variable actions.

The verification for fatigue is conducted by evaluating the stresses that induced by the fatigue load model specified by the Eurocode.

However, the UK National Annex for Eurocode 2, recommends exempting the effect of fatigue, if clear span to overall depth ratio of the slab is not exceeding 18.

Under these circumstances, verification and analysis of fatigue traffic loads models are not accounted for in this study and generally not applicable in box culvert design.

2.3.3 Dynamic Effects

2.3.3.1 Dynamic Amplification Factors (DAF)

Owing to moving traffic, highway structures are subjected to dynamic effects, and this is accounted by Eurocode via Dynamic Amplification Factor (DAF) and denoted by ψ. The DAF is governed by several factors given below but not limited to same;

- The Type of Bridge
- Span of the Bridge
- The Natural frequency of the Bridge
- The damping coefficient of the bridge
- Dynamic characteristic of the traffic loads and vehicle speed
- The road pavement roughness

When natural frequencies of the bridge and frequencies of vehicular axels (10 to 12 Hz) and vehicles (1 to 2 Hz), are too closer, the effect of dynamic amplification is higher (Sanpaolesi and Croce, 2005, Paeglite and Paeglitis, 2013).

The load model in Eurocode has an in built DAF. The below Figure 8 depicts the in-built factors.

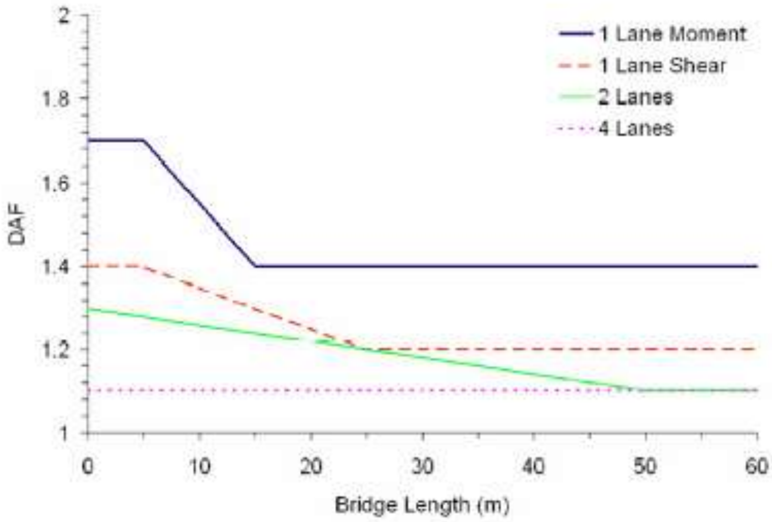


Figure 8 : In-built DAF for Load Models in EC (Atkins, 2004)

The country-specific studies allow fine-tuning of DAF and will pave the way to more realistic values (Atkins, 2004).

Further, LM1 to LM 4 includes an additional dynamic amplification factor ($\Delta\psi_{fat}$), defined by cl 4.6.1(6), BS EN 1991-2, as shown by Figure 9 ,accounting for pavement of good quality and applicable conservatively as 1.3 in cross-sections near to the expansion joints with 6m.

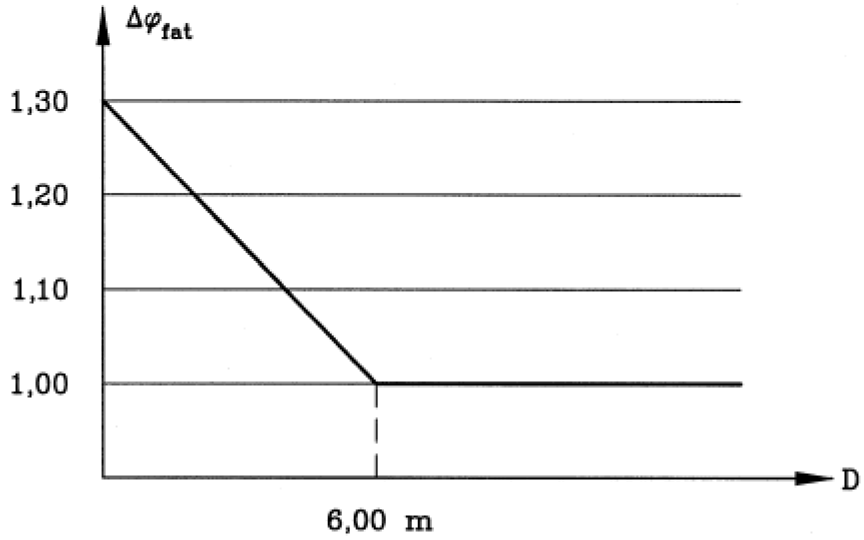


Figure 9 . Additional Dynamic Amplification Factor (BSI, 2004)

2.3.4 Temperature Effects

As per DMRB guidelines, the stresses generated owing to temperature are considered unless the earth cover to the structure is high or overall length of the structure is less than 3m.

The stresses owing to temperature are originated owing to two different reasons.

1. Variation in mean temperature (Temperature Range)
2. The temperature within the section (Differential Temperature)

Temperature Range

BD 31/01 (DMRB) gives the guidelines on Temperature range that has to be incoporated in to burried box structures as shown in Figure10.

	Temperature Range	
	For Expansion	For Contraction
Box structures	10°C to T_{max}	10°C to T_{min}
Precast Portal frames	0°C to T_{max}	20°C to T_{min}
In-situ Portal frames	10°C to T_{max}	30°C to T_{min}

Figure 10 :Temperature Range specified by DMRB

Here T_{max} and T_{min} are the effective maximum and minimum temperatures of the roof.

Differential Temperature

BD 31/01 (DMRB) gives the guidelines on Differenctial Temperature that has to be incoporated to burried box structures and the Figure 11 is depiciting the same.

Span to Width Ratio	Cover	Minimum and maximum effective temperature		Differential temperature	
				Temperature difference	Reduction factor
X_{clear}/L_{t}	H (m)	T_{min}	T_{max}		η
≥ 0.2*	All depths	In accordance with BD 37		In accordance with BD 37**	N/A
< 0.2	H ≤ 0.6	In accordance with BD 37		In accordance with BD 37**	N/A
	0.6 < H ≤ 0.75	0°C	20°C	From BD 37, Figure 9, Group 4	0.5
	0.75 < H ≤ 1.0	4°C	16°C	From BD 37, Figure 9, Group 4	0.33
	1.0 < H ≤ 2.0	7°C	13°C	From BD 37, Figure 9, Group 4	Zero
	H > 2.0m	Temperature effects may be neglected			

Figure 11 : Temperature Range specified by DMRB for Box culverts

2.3.5 Accidental Load Cases

The accident loads define in Eurocode refers to general cases and given in equivalent static load cases. Cl 2.3 , BS EN-1991-2 (BSI, 2004)

2.3.6 Shrinkage

Both in Eurocodes as well as in BS 5400, the loads owing to concrete shrinkage are considered as a permanent load.

However, DMRB guidelines on Box Culvert is silent on the shrinkage generated stresses, and the effects are not considered in its recommended load combinations. It is apparent that when determining the datum temperatures and stresses owing to mean temperature differences, the effects owing heat of hydration and shrinkage effects are also incorporated (cl b(1) , 3.2.8 DMRB guidelines).

2.3.7 Partial Safety factors

The use of partial safety factors in design is a semi probabilistic approach that is widely used in design standards. It increases the safety of the structure while reducing the probability of failure of the structure either in ULS or SLS (Monteverde, 2017).

The following table summarises the description, symbol, and relevant clause of reference for partial safety factors adopted (Monteverde, 2017)

Table 3 : Summary of Partial Safety Factors in Eurocode & BS (Monteverde, 2017)

	Description	Eurocode	BS 5400
Actions/ Loads	Applied to cater uncertainty in applying loads or actions	Y_F – EN 1990-1, Annex 2 ULS: Y_G -permanent Actions = 1.35 Y_Q - Variable Action =1.5	Y_{fl} ULS: Y_{fl} - Concrete self wt. = 1.15 Y_{fl} Steel self wt = 1.05 Y_{fl} Surfacing = 1.75 Y_{fl} Other Loads = 1.2 Y_{fl} Live Loads = 1.5
Materials	Accounted for an uncertainty of the Material	Y_m - EN 1990-1, Cl 6.3.5 Concrete (persistent/transient)= 1.5 Steel (persistent/transient)= 1.15 Concrete (accidental)= 1.2 Steel (accidental)= 1.0	Y_m Cl 4.3.3.3 Part 4 :BS 5400 Concrete = 1.5 Steel = 1.15
Assessment	Accounted for in accurate assessment	Not Applicable	Y_{f3} = 1.1 cl 2.3.2 part 1 : BS 5400

2.4 UK practice for National Annex

UK national annex to EN1990 has been developed to integrate with the BS 5400:2006 – part 2 (Atkins, 2004).

HA loading in BS 5400 (2006) has been considered a reasonable basis for the calibration of α factors (Atkins, 2004). As discussed previously, Eurocode has different intensities for UDL in Load Model 1, which contrasts with BS practice. The advantage of using a constant UDL for each lane is that it enhances the simplicity of analysing the bridge for critical loads (Atkins, 2004). In UK national annex to Eurocode, this has been achieved by changing the α to provide ULS design UDL of 7.425 kN/m^2.

The resulted α values of UK national annex and EN 1991-2 values are provided in Table 4.

Table 4 : National Parameters LM1 of UK to Eurocode (BSI, 2004)

Lane	EN 1991-2		UK National Annex		Minimum Recommended by EN 1991-2	
	TS (kN)	UDL (kN/m^2)	TS (kN)	UDL (kN/m^2)	TS (kN)	UDL (kN/m^2)
Lane 1	1.0	1.0	1.0	0.611	0.8	0.8
Lane 2	1.0	1.0	1.0	2.2	No restriction & as per NA	1.0
Lane 3	1.0	1.0	1.0	2.2	No restriction & as per NA	1.0
Other	N/A	1.0	Not Applicable	2.2	N/A	1.0
Remaining Area	N/A	1.0	Not Applicable	2.2	N/A	No restriction & as per NA

2.4.1 Load Combination

The recommendation of UK national annex on load combinations have been provided to integrate with BS 5400 part 2 or DMRB BD 37. Generally, more than two variable loads for single combination are not accounted, owing to a low probability of occurrence.

In line with this, the UK national annex NA 2.3.3.3, NA 2.3.3.4, NA 2.3.4.1, NA 2.3.4.2, recommends that combinations of the snow load along with wind and temperature may be ignored.

2.5 Chapter Summary

The Box structures are very economical structures to concur obstacles meet in highways and expressways in the form of either water path or vehicular traffic. The box culverts are made of concrete and steel. Many codes of practices are availed for design of highway structures and box culverts.

The Eurocode of practice for design of concrete box structures are based on Eurocode 1 and Eurocode 2. The practice of Eurocode is different from previously adopt BS practice where below key concepts are highlighted.

- Design Situations
- Reversible and Irreversible Limit State
- Representative values of variable actions
- Six Limit states
- Single Source of Principle
- Combinations of actions

In addition to the above conceptual differences, the other differences such as determinations of notional lanes, load intensities, load distributions in lanes, partial safety factors, etc, have been discussed in detail.

Then major design concepts adopted in Box structures are discussed in subsequent sub sections. This is included with construction stage analysis, fatigue and dynamic effects, temperature effects, accidental and shrinkage loads.

Lastly the UK practice of adopting Eurocode for design of highway structures are scrutinised. Here the UK National Annex for Eurocode is studied with respect to its load models and combinations of actions.

3.0 Analysis for Eurocode Load

3.1 Box Structure Dimensions

Various configurations of concrete box culverts were modelled using commercially available finite element software - MIDAS Civil and various sizes of single-cell box culverts were selected to study the effects of traffic loading, as shown in Table 5;

Table 5 : Configurations of Box Culvert for FE Models

	Clear Height (m)	Clear Span (m)	Wall, top & Bottom Slab Thicknesses (mm)
1x1 Box	1	1	200
1.5 x 1.5 Box	1.5	1.5	200
2x2 Box	2	2	200
3x3 Box	3	3	300
4x4 Box	4	4	400
4.5 x4.5 Box	4.5	4.5	450
5x5 Box	5	5	500
5.5 x5.5 Box	5.5	5.5	550
6x6 Box	6	6	600
7 x7 Box	7	7	700
8 x8 Box	8	8	800

The finite element models are built for each above box culvert configuration using plate elements. These plate elements are consisting of 4 nodes in one single plane. The plate element in MIDAS CIVIL can provide the structural response for membrane forces, in plane & out of plane shear forces and out of plane bending moments.

3.2 The Loading from Eurocode

The load models in Eurocode which simulate the traffic load are limited to 200m of loaded length. In BS 5400, the loaded lengths are limited to 1600m, and where this limit is exceeded, the loading shall be agreed with the relevant authority.

However, NA to BS EN 1991-2 :2003, the National Annex to UK, recommends LM 1 to be used for a loaded length up to 1500m (BSI, 2008).

The load models in Eurocode for vertical loads are given as below;

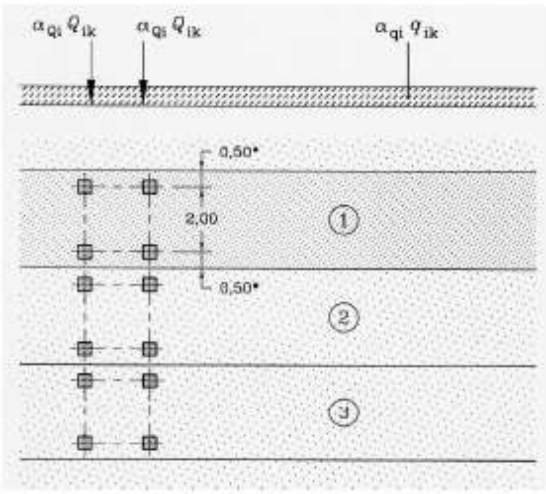
3.2.1 Load Model 1 (LM 1) – This traffic model covers the general traffic on a road way which consists of lorries and cars. This is simulated by a combination of concentrated load and a uniformly distributed load as given by Figure 12. The concentrated load is generally identified as Tandem Load (TS). The TS in LM1 is a two-axel load (BSI, 2004).

The load intensities covers by the LM1 represent heavily loaded lorries in congested traffic situation (Atkins, 2004).

LM1 is Included an adjustment factor α. When α=1, it corresponds to heavy industrial international traffic. For common traffic composition, a moderate reduction of α, 10% to 20% can be adopted via National Annexure

Location	Tandem system *TS*	*UDL* system
	Axle loads Q_{ik} (kN)	q_{ik} (or q_{rk}) (kN/m^2)
Lane Number 1	300	9
Lane Number 2	200	2,5
Lane Number 3	100	2,5
Other lanes	0	2,5
Remaining area (q_{rk})	0	2,5

The details of Load Model 1 are illustrated in Figure 4.2a.



Key
(1) Lane Nr. 1 : Q_{1k} = 300 kN ; q_{1k} = 9 kN/m^2
(2) Lane Nr. 2 : Q_{2k} = 200 kN ; q_{2k} = 2,5 kN/m^2
(3) Lane Nr. 3 : Q_{3k} = 100 kN ; q_{3k} = 2,5 kN/m^2
* For w_l = 3,00 m

Figure 12 : Load Model 1 defined by Eurocode (BSI, 2004)

The characteristic values of Q_{ik} and q_{ik} , are included with DAF (BSI, 2004)

.

Simplified Load Model to LM 1

Since load values in each tandem in LM1 are varying, this will give tedious work in evaluating the structural effects. In this regard , the Eurocode allows a simplified load model. It allows to replace the 2nd and 3rd tandem system with similar to 1st tandem system. (BSI, 2004, p. 38). However this is allowed , if it is permitted by the National Annex (NA) . In NA to UK is not permitting this

3.2.2 Load Model 2 (LM 2) – This is to cover the dynamic effects of the normal traffic on short structural members. This includes a single axel load and an NDP, βQ . LM 2 consist of a single axle load βQ Qak with Qak =400kN as shown in Figure 13. This is also included with dynamic amplification Factor (DAF) (BSI, 2006) .

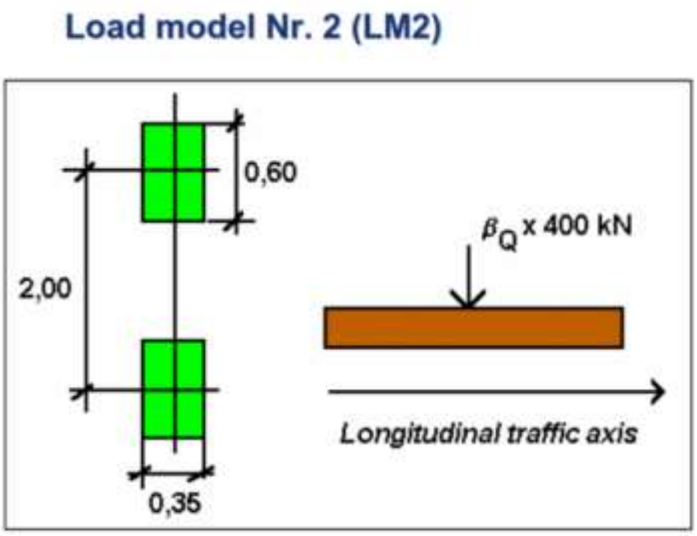


Figure 13 : Graphical depiction of LM 2 (Calgaro, 2008)

3.2.3 Load Model 3 (LM 3) – This load model represent the special vehicle or abnormal vehicle which may allowed to operate under special approval of the road managing authority. This model consist of several axel loads and defined as a Nationally developed parameter (NDP) . Therefore relevant axel arrangement should be included in the National Annex (NA) (BSI, 2006).

In conjunction with UK practice, the SV 80 is selected as LM 3 for this study and the details of SV 80 is shown in Figure 14 and Figure 15 (BSI, 2008). This is on par with the traffic load case HB 30 defined in BS 5400 (2)-2006(Seyanthan and Jayasinghe, 2013).

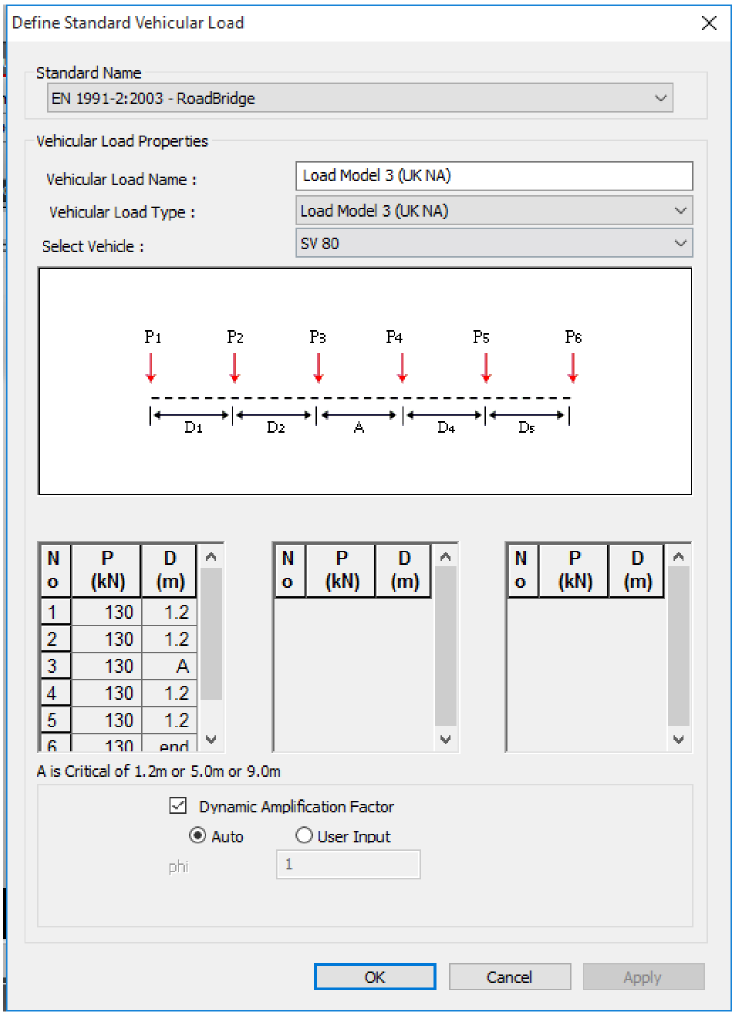


Figure 14 : Graphical depiction of LM3, , MIDAS CIVIL

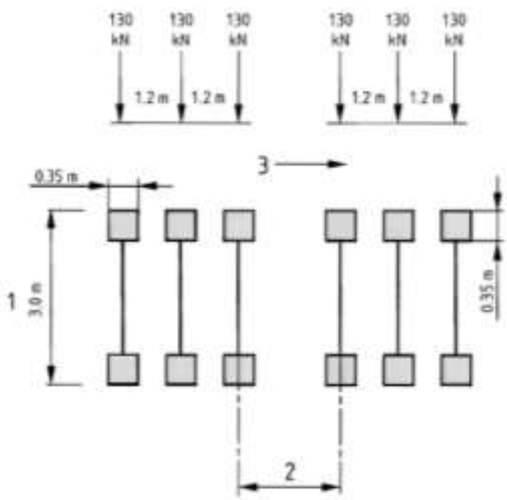


Figure 15 : Detail of SV 80 used in Load Model 3 (BSI, 2004)

3.3 The Load Combination Eurocode

Though combinations of actions given in Eurocode are complex than of BS 5400, the Annex A2 of EN 1990: Application of Bridges (Normative) provide supplementary rules for load combinations (BSI, 2004).

In conjunction with above Annex, the Snow and Wind Actions are not required to combine with

- The horizontal loads such as braking , acceleration and centrifugal forces and group of loads in gr 2.
- The vertical loads induced by the footways & cycle track loads and group of loads in gr 3
- The vertical loads of crowd loading in gr 4 (CEN, 2005)

Further, in conjunction with cl. A2.2.2(2), Annex A2- BS EN 1990, Load Model 2 (LM2) and its load group gr1b is not required to combine with other variable loads which are not occurring owing to traffic (CEN, 2005).

Lastly , the Wind Action and Thermal Actions are not required to combine together and not considered simultaneously (CEN, 2005).

In above context, the following load combinations are considered for ULS, STR verification in conjunction with table A2.4(B), ANNEX A2, BS EN 1990;

$1.35\ G_{kj,\ sup} + 1.0\ G_{kj,inf} + 1.35\ (TS+UDL+q_{fk}) + 1.5x\ 0.6T_k$

$1.35\ G_{kj,\ sup} + 1.0\ G_{kj,inf} + 1.35\ gr_{1b}$

$1.35\ G_{kj,\ sup} + 1.0\ G_{kj,inf} + 1.35\ gr_2 + 1.5x\ 0.6T_k$

$1.35\ G_{kj,\ sup} + 1.0\ G_{kj,inf} + 1.35\ gr_5$

$1.35\ G_{kj,\ sup} + 1.0\ G_{kj,inf} + 1.5xT_k + 1.35x(0.75\ TS + 0.4\ UDL + 0.4\ q_{fk})$

The TS and UDL indicate the tandem system in LM 1, and q_{fk} is the combined value of the crowd loading. T_k refers to temperature loadings. The load groups (gr1a, gr1b etc.,) is referred to table 4.4a, BS 1991-2 as reproduced below table 6.

Table 6 : Group of Traffic Loads (BSI, 2004).

		CARRIAGEWAY						FOOTWAYS AND CYCLE TRACKS
Load type		Vertical forces				Horizontal forces		Vertical forces only
Reference		4.3.2	4.3.3	4.3.4	4.3.5	4.4.1	4.4.2	5.3.2-(1)
Load system		LM1 (TS and UDL systems)	LM2 (Single axle)	LM3 (Special vehicles)	LM4 (Crowd loading)	Braking and acceleration forces	Centrifugal and transverse forces	Uniformly Distributed load
Groups of Loads	gr1a	Characteristic values				[a]	[a]	Combination value [b]
	gr1b		Characteristic value					
	gr2	Frequent values[b]				Characteristic value	Characteristic value	
	gr3 [d]							Characteristic value [c]
	Gr4				Characteristic value			Characteristic value [b]
	Gr5	See annex A		Characteristic value				
	Dominant component action (designated as component associated with the group)							

[a] May be defined in the National Annex.
[b] May be defined in the National Annex. The recommended value is 3 kN/m^2.
[c] See 5.3.2.1-(2). One footway only should be considered to be loaded if the effect is more unfavourable than the effect of two loaded footways.
[d] This group is irrelevant if gr4 is considered.

The combination of the actions for SLS verification in conjunction with table A2.6, ANNEX A2, BS EN 1990 is as follows;

Characteristic combination of actions;

$$G_{kj,\,sup} + (TS+UDL+q_{fk}) + 0.6T_k$$

$$G_{kj,\,sup} + gr1b$$

$$G_{kj,\,sup} + gr2 + 0.6T_k$$

$$G_{kj,\,sup} + gr5$$

$$G_{kj,\,sup} + T_k + (0.75\,TS + 0.4\,UDL + 0.4\,q_{fk})$$

The frequent Combination of actions become

$$G_{kj,\,sup} + (0.75TS+0.4UDL+0.4q_{fk}) + 0.5T_k$$

$$G_{kj,\,sup} + 0.75gr1b$$

$$G_{kj,\,sup} + 0.6T_k$$

The quasi-permanent combination is

$$G_{kj,\,sup} + 0.5T_k$$

3.4 The Loading from BS

In view of simulating the normal traffic on highways, the part 2 of BS 5400 introduces HA loads. HA consists of a uniformly distributed load and a knife-edge load. The UDL of the HA is defined in conjunction with the loaded length as depicted below in Figure 16.

The UDL defined in the 1978 version of part 2 and 2006 version of part 2 are different. The 2006 version is providing higher UDL for shorter spans than the 1978 version.

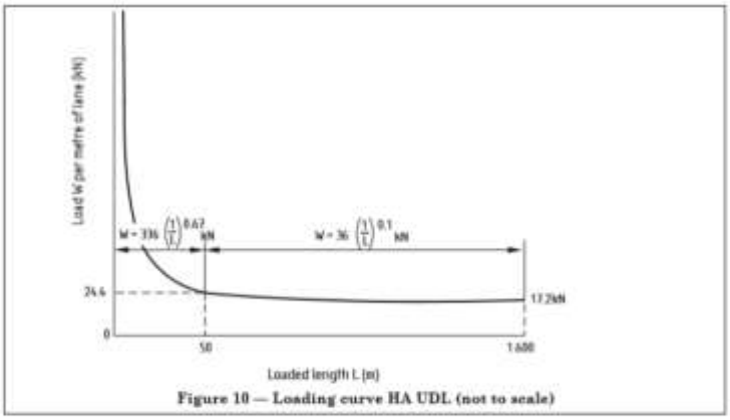


Figure 16 : BS 5400 HA UDL (BSI, 2006)

KEL is taken as 120 kN per notional lane as defined in clause 6.2.2 , part 2, BS 5400 (BSI, 2006).

In view of applying HA loading, the below UDL values given by Table 7 and Table 8 are derived for different configurations of box structures.

Table 7 : HA UDL Intensities (BS 5400 part 2, 2006), for different Box Structures

Box Configuration	1.0 x 1.0	1.5x1.5	2x2	3x3	4x4	4.5x4.5	5x5	5.5 x5.5	6x6	7x7	8x8
thickness mm	200	300	200	300	400	450	500	550	600	700	800
clear span	1	1.5	2	3	4	4.5	5	5.5	6	7	8
effective span	1.2	1.8	2.2	3.3	4.4	4.95	5.5	6.05	6.6	7.7	8.8
HA UDL 2006 kN/m per NL	336.0	256.1	211.2	160.9	132.7	122.7	114.3	107.2	101.2	91.2	83.4
HA UDL 2006 kN/m2	90.8	69.2	57.1	43.5	35.9	33.2	30.9	29.0	27.3	24.7	22.5

Table 8 : HA UDL Intensities (BS 5400 part 2, 1978), for different Box Structures

Box Configuration	1.0 x 1.0	1.5x1.5	2x2	3x3	4x4	4.5x4.5	5x5	5.5 x5.5	6x6	7x7	8x8
thickness mm	200	300	200	300	400	450	500	550	600	700	800
clear span	1	1.5	2	3	4	4.5	5	5.5	6	7	8
effective span	1.2	1.8	2.2	3.3	4.4	4.95	5.5	6.05	6.6	7.7	8.8
HA 1978 kN/m per loaded length	30	30	30	30	30	30	30	30	30	30	30
HA 1978 UDL kN/m2	8.11	8.11	8.11	8.11	8.11	8.11	8.11	8.11	8.11	8.11	8.11

In view of simulating the abnormal vehicle which may occur in a highway, the HB vehicle is defined with certain number of units. The number of units that required to considered for particular road is varying base on its importance. Generally, the number of HB units are defined by the road authority which particular road system is owned or managed. The single unit of HB is equal to 10 kN per axel, and the Bridge Design Manual of RDA, Sri Lanka, recommends 30 units of HB for class A & B roads in Sri Lanka. Since, HB vehicle consists of 4 axels, as shown in Figure 17, the total load of the HB equals to 30 x 10 x 4 =1200 kN of load.

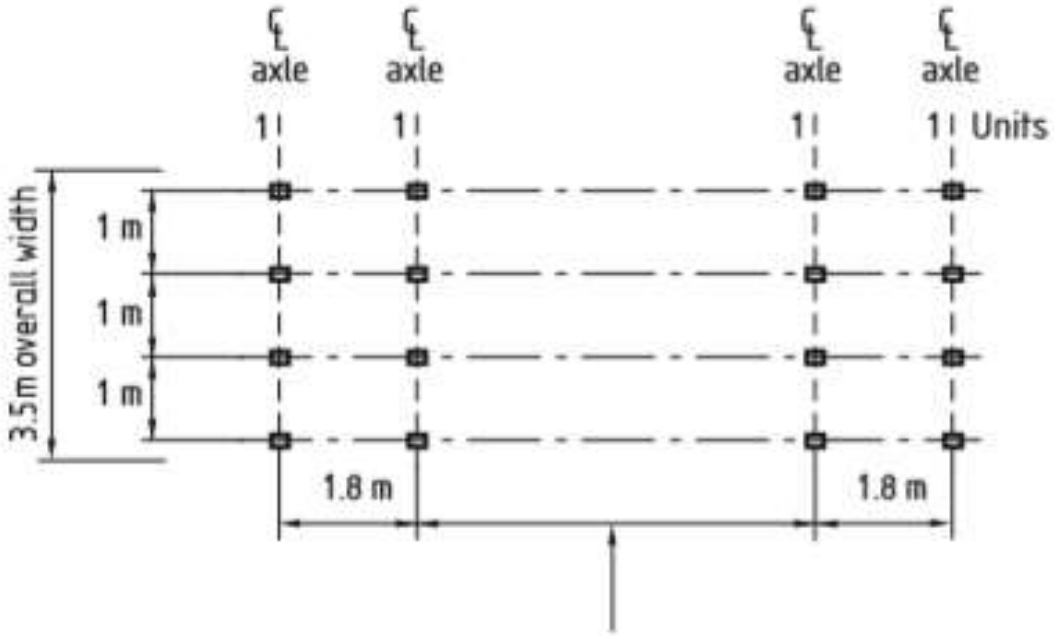


Figure 17 : BS 5400, HB Load (BSI, 2006)

The number of HB units recommended by DMRB for roads in UK is as Table 9 below.

Table 9 : HB units in UK

Type of Roads	**Recommended HB Units**
Motorway and trunk Road	45 Units
Principle road	37.5 Units
Public Road	Minimum of 30 Units

The longitudinal load owing to traction or the braking of the vehicles is defined by the clause 6.10, part 2 of the BS 5400. Accordingly, the HA traction load shall be taken as 8 kN/m of loaded length plus 250 kN (BSI, 2004).

Table 10 : HA Traction intensities

Box Configuration	1.0 x 1.0	1.5x1.5	2x2	3x3	4x4	4.5x4.5	5x5	5.5 x5.5	6x6	7x7	8x8
thickness mm	200	300	200	300	400	450	500	550	600	700	800
clear span	1	1.5	2	3	4	4.5	5	5.5	6	7	8
HA traction 2006	258	262	266	274	282	286	290	294	298	306	314
Kn/m2	58.1	39.3	32.7	22.4	17.3	15.6	14.3	13.1	12.2	10.7	9.6

The traction load owing to HB type traffic load is taken as 25% of the nominal HB vertical load adopted. This is equally distributed among the 8 wheels of 4 axels.

3.5 The Load Combinations of BS

The effects of actions are not occurring simultaneously always owing to various reasons. The BS 5400 and Eurocode both incorporate this concept of combination of actions. In BS 5400 (2), five load combinations are defined as below (BSI, 1978);

- Combination 1 – All permanent loads are accounted together with vertical live loads. The wind & temperature loads are neglected.

  HA ULS - 1.1 x (1.15 DL+ 1.75 SIDL +1.5 Soil + 1.5 HA UDL& KEL)

  HA SLS - 1.1 x (DL+ 1.2 SIDL + Soil + 1.2 HA UDL& KEL)

  HB ULS - 1.1 x (1.15 DL+ 1.75 SIDL +1.5 Soil + 1.3 HB)

  HB SLS - 1.1 x (DL+ 1.2 SIDL + Soil + 1.1 HB)

Combination 2 - All permanent loads are accounted together with vertical live loads. The wind loads are accounted but not Temperature.

Combination 3 - All permanent loads are accounted together with vertical live loads. The Temperature loads are accounted but not Wind.

HA ULS - 1.1 x (1.15 DL+ 1.75 SIDL +1.5 Soil + 1.25 HA UDL& KEL +1.3 Tk)

HA SLS - 1.1 x (DL+ 1.2 SIDL + Soil + 1.0 HA UDL& KEL + Tk)

HB ULS - 1.1 x (1.15 DL+ 1.75 SIDL +1.5 Soil + 1.1 HB+1.3Tk)

HB SLS - 1.1 x (DL+ 1.2 SIDL + Soil + 1.0 HB+Tk)

Combination 4 - All permanent loads are accounted together with vertical and horizontal live loads. The Temperature & Wind loads are not accounted.

HA ULS - 1.1 x (1.15 DL+ 1.75 SIDL +1.5 Soil + 1.25 HAUDL& KEL+1.25HA traction)

HA SLS - 1.1 x (DL+ 1.2 SIDL + Soil + HA UDL& KEL+HA traction)

HB ULS - 1.1 x (1.15 DL+ 1.75 SIDL +1.5 Soil + 1.1 HB+1.1 HB Traction)

HB SLS - 1.1 x (DL+ 1.2 SIDL + Soil + HB+HB Traction)

Combination 5 - All permanent loads are accounted together with temperature loads for bearing.

3.6 Notional Lane

The selection of the cross-section for the road is a very important factor as the number of notional lanes depends on this. As shown in Figure 18, both in Eurocode as well as in BS 5400, the carriageway is defined, generally, as the distance between the kerbs of foot walk. This is a widely used articulation in A and B class roads of Sri Lanka.

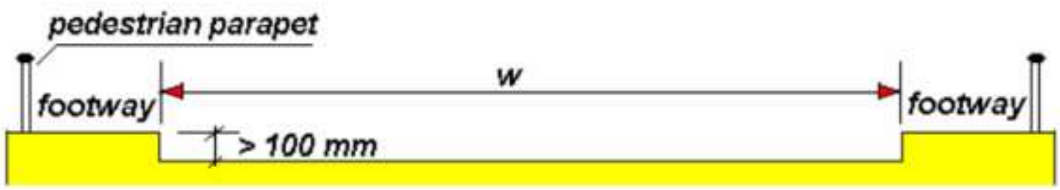


Figure 18 : Carriage way definition

The lane definition in Eurocode is provided in Figure 19. Here , width of lane is 3m except for carriageway width 5.4m to 6m.

Based on the width of the carriageway, the number of notional lanes varies. However, a significant difference exists between the two codes. The number of notional lanes in BS 5400 is always a whole number as shown in Figure 20. But in Eurocode, the remaining area after allocating space for notional lanes is considered for loading.

The definition given in the Eurocode for Remaining Area is as follows.

“ Difference, where relevant, between the total area of the carriage way and the sub of the areas of the notional lanes”

(BSI, 2003)

Though the concept of the remaining area is unfound in BS, it accounts for the width between raised kerbs, including hard shoulders. The same is divided as per the intended number of notional lanes, where all the spaces between two raised kerbs are included in each notional lane.

The most common configuration of Sri Lankan roads is 2 road lanes of 3.7 m width in both way traffic, which account for 7.4 m width of carriage way.

Carriageway width w	Number of notional lanes	Width of a notional lane w_l	Width of the remaining area
$w < 5{,}4$ m	$n_l = 1$	3 m	w - 3 m
$5{,}4$ m $\leq w < 6$ m	$n_l = 2$	$\frac{w}{2}$	0
6 m $\leq w$	$n_l = Int\left(\frac{w}{3}\right)$	3 m	$w - 3 \times n_l$
NOTE For example, for a carriageway width equal to 11m, $n_l = Int\left(\frac{w}{3}\right) = 3$, and the width of the remaining area is 11 - 3×3 = 2m.			

Figure 19 : Notional Lane guideline given in Euro Code (BSI, 2004)

carriageway width m	number of notional lanes
4.6 up to and including 7.6	2
above 7.6 up to and including 11.4	3
above 11.4 up to and including 15.2	4
above 15.2 up to and including 19.0	5
above 19.0 up to and including 22.8	6

Figure 20 : Notional Lane guideline given in BS (BSI, 2006)

Therefore, the number of notional lanes assessed as per BS would be 2, and the width of the notional lane would be 3.7m

But in conjunction with Eurocode, the number of notional lanes would be 2 with 3m width and the remaining area would be 1.4m(7.4-3*2=1.4m)

Thus, widely seen lane configuration of Sri Lanka, which is two lanes of 3.7m and 1.5m wide two raised foot walks on both sides, will be considered in this exercise.

Adopted lane details for this study are depicting in Figure 21.

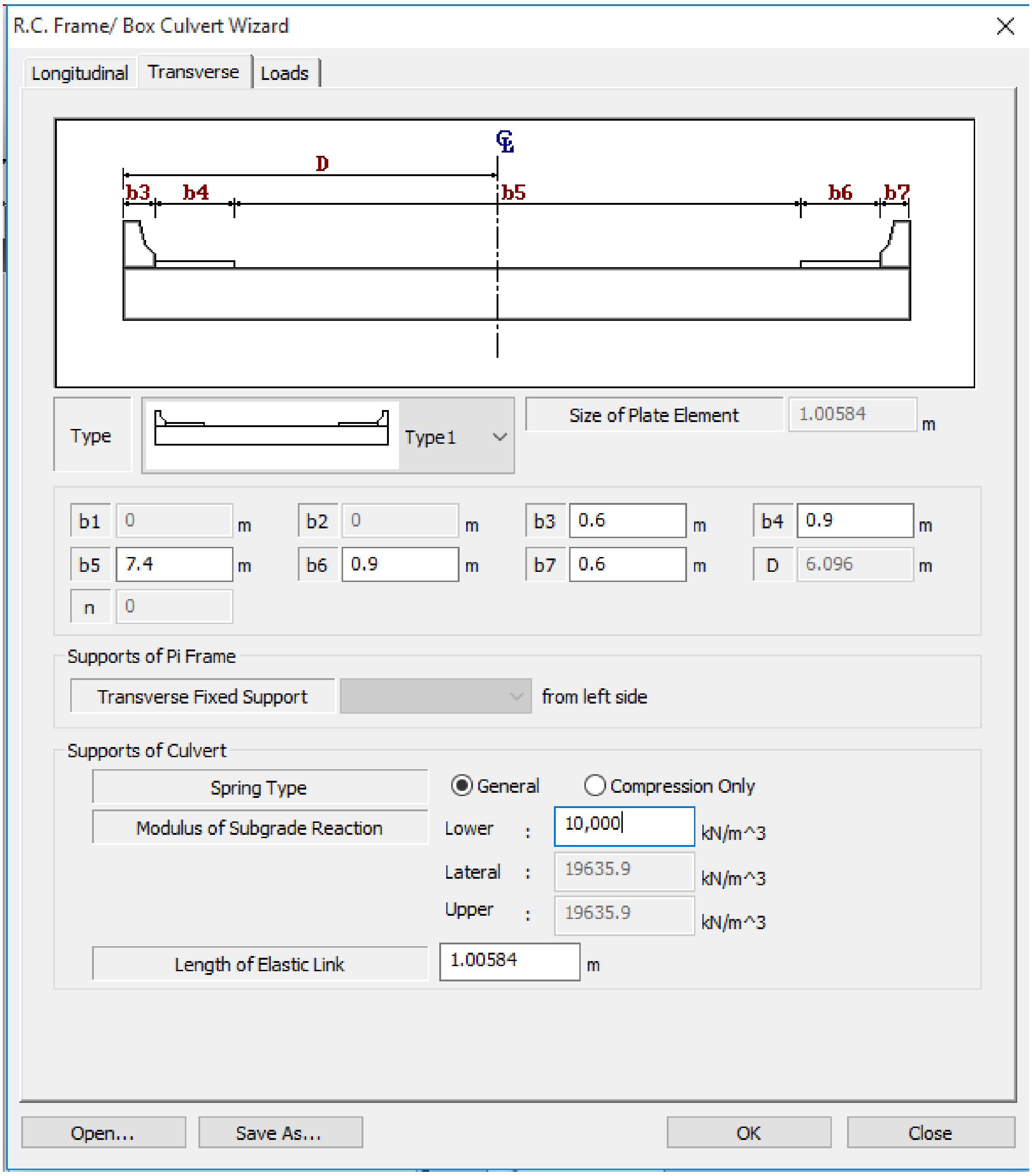


Figure 21 : Define of Road Width MIADS CIVIL

A significant difference of the Eurocode from the BS is that its emphasis on lane numbering, where BS is not specifying a lane number. In Eurocode, the lanes are numbered but these are not marked in chronologically. Instead, lane 1 is marked where most unfavourable effects are produced. The 2^{nd} lane is producing the second most severe traffic effects. The remaining lanes are marked with same concept (BSI, 2004, p. 34). This is further shown in Figure 22.

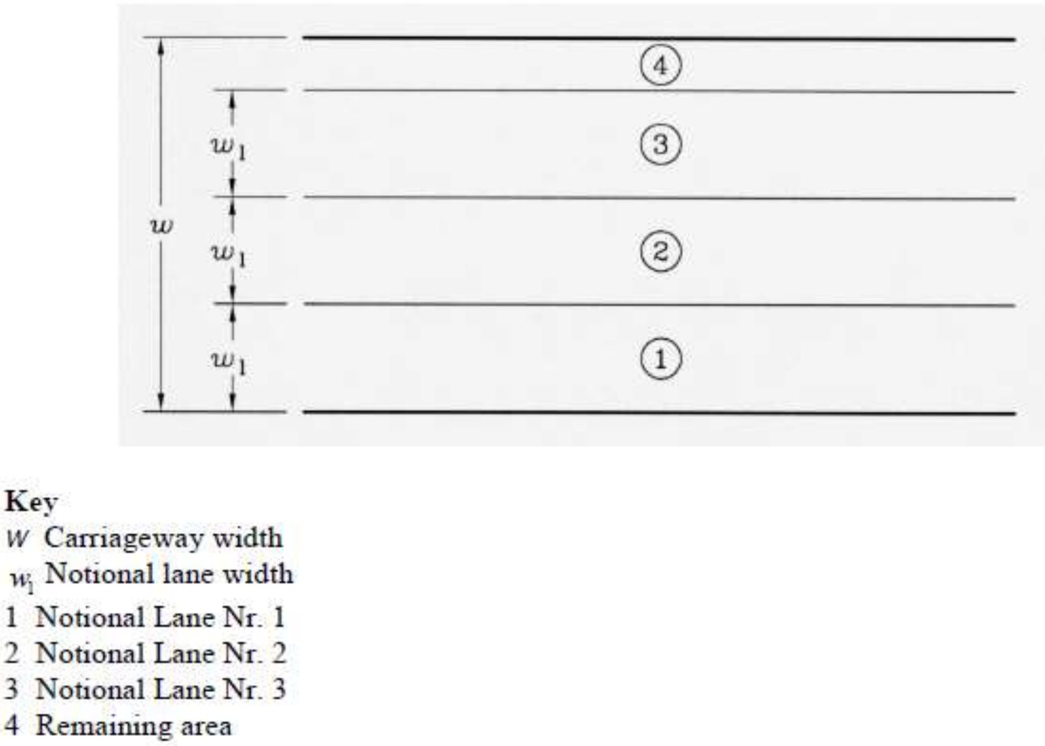


Figure 22 : Lane Numbering in Eurocode (BSI, 2004)

3.7 The Structural Idealization

The manual methods of analysing box culverts are based on 2-dimensional plane frame analysis with external supports. The boundary conditions of the model are comprised with simple support and a roller support at the bottom foundation as depicted in Figure 23 (MDOT, 2013)

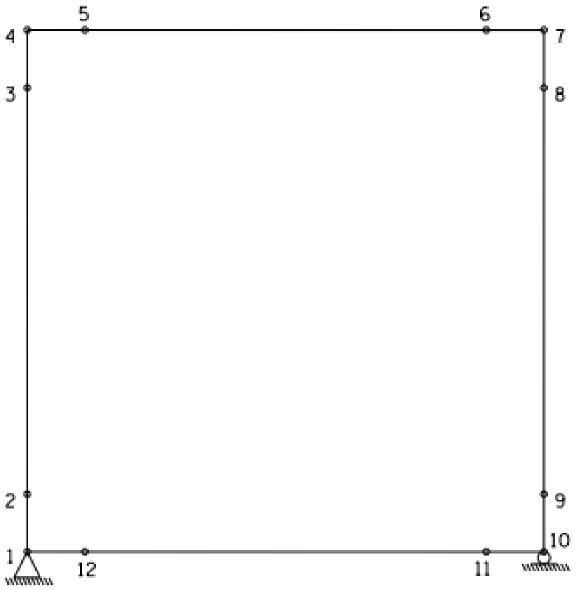


Figure 23 : 2D Frame Analysis

Source : (MDOT, 2013)

BD 31/ 01, DMRB accept the adequacy of 2-dimensional analysis, a unit width method but also accept the three-dimensional methods and recommends considering the interaction of the live loads in adjacent lanes (DMRB, 2001). It is general practice to consider the unit width of the culvert with associate loads and analyse it as a frame (Tikate and S.N.Tande, 2015).

BD 31/ 01, DMRB guidelines allow to analyse the box culvert as a 2D frame with pin joints where walls are not fully integrated with slab and foundations. Furthermore, it provides liberty for designer to consider the stiffness of the fillets (DMRB, 2001). However, unlike MDOT guidelines, where it recommended to take pin and roller supports at the nodes of foundation strip, DMRB does not spell out the boundary conditions at foundations explicitly other than making the difference between rigid and flexible behaviour of the foundation. In the case of flexible types, it suggests using elastic compressible supports.

3.7.1 Finite Element (FE) Model

The Finite-element technique has become the most widely accepted numerical technique in engineering analysis. Many types of Finite Element models based on frame, plate or solid element are in practice in modern day box culvert analysis. It is therefore important to decide the appropriate model that suits this study..

The FE models have been used successfully to predict the structural effects of box culverts of different kinds. The study on aluminium box culverts has shown that the results of the FE model agree with the actual experimental results. Even for a material like Aluminium where high sensitivity observed for soil back fill owing to relative low stiffness of the Aluminium wall , it shows that FE model is a good tool to predict the actual scenario(Abdel-Haq, 1987).

On another study which has conducted on concrete box culverts that rest on geogrid reinforced gravel fill has shown that values derived by FE model for deferential settlement are on par with experimental results obtained (Shivashankar, 1995)

The study of Tikate and S.N Tande,2015, an analytical research on the soil cushion on box culverts & distribution of loads, has concluded that the results of the FEM, are in close relation with the manual calculations. FE has been based on STADD Pro software. Manual output has obtained with the moment distribution analysis which is specified in the IS code practice. In this study, FE model is a frame structure and it simulates a single cell box culvert (Tikate and S.N.Tande, 2015).

In this sturdy, the box structures were modelled using 4 node plate elements as shown in Figure 24. The thickness of the plate was taken to suit the different span of the box configuration to accommodate the serviceability requirements and optimise the deflections.

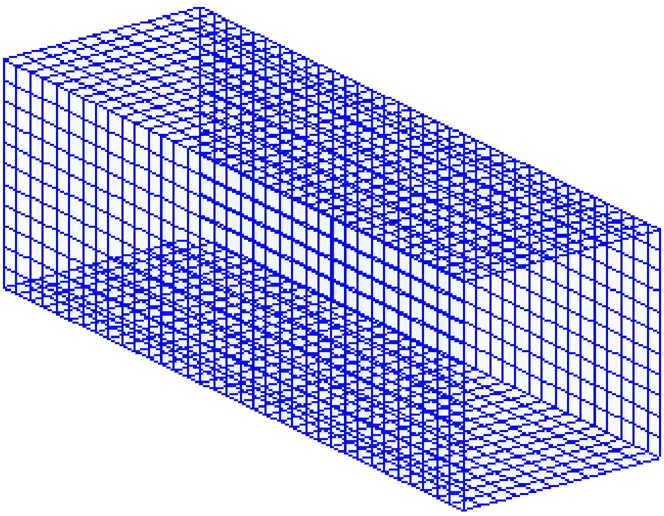


Figure 24 : 3D Model of the 3x3 Box Culvert

The structures are being modelled using commercially available FE software MIDAS CIVIL. The structural actions of the 4 node plate elements are defined as Figure 25.

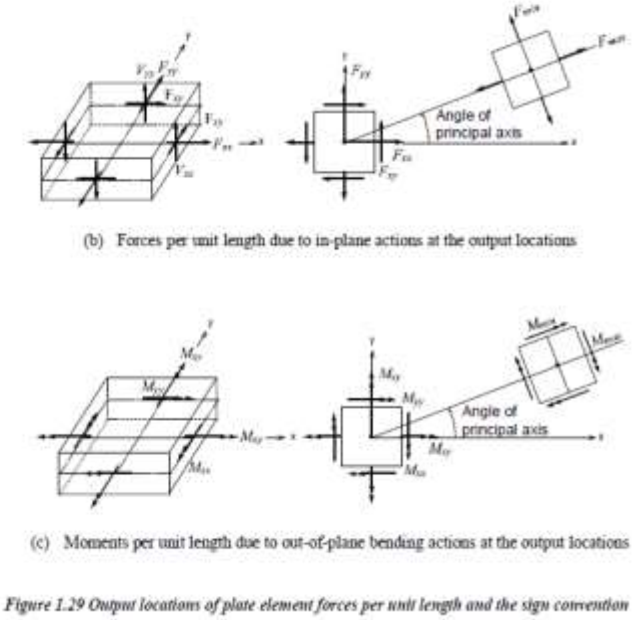


Figure 25 : Sign Convention used in MIADS CIVL

The results are given with respect to the element local coordinate system defined as in Figure 26.

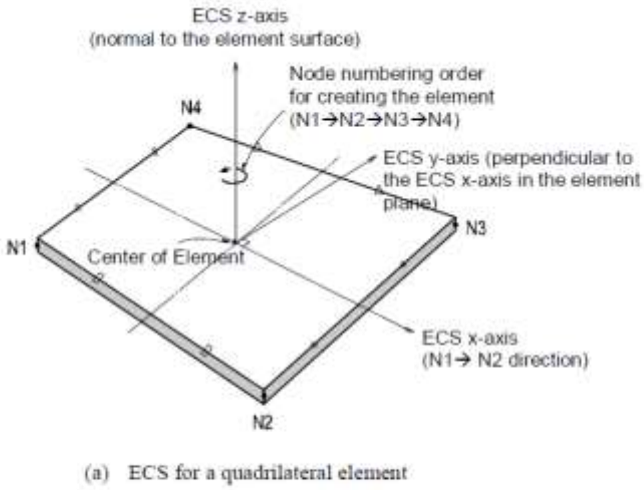


Figure 26 : Axis definition for Plate elements in MIDAS CIVIL

3.7.2 Finite Element Mesh Density

In structural analysis software, the Numerical Methods are integrated to solve the equilibrium problem and thereby provisioning of structural responses. The most widely adopted Numerical Methods are known as , Finite Element Methods, Boundary Element Methods, Finite Volume methods and Meshless methods.

Among these, the Finite Element Method (FEM) is most used and has been adopted as the analysing technique for Midas Civil, the structural software used in this study.

In FEM, the structure is divided into small elements which are called finite elements. The connections between these elements are defined based on the compatibility relationships between the relevant nodes of the elements. Since the adjacent elements share the same degree of freedom at connecting nodes, the simultaneous equations, derived based on the compatibility, are used to interpolate the displacements of the entire structure.

When structure is dividing into small elements, the size of the elements, generally known as mesh density, will affect the accuracy of the results. The higher density provides the much accurate results. However, the drawback is that it will utilize a greater computer memory and may resulted with long analysis duration or computer memory crashes. Thus, finding the optimum mesh density is vital in finite element methods.

If theoretical or test results of a structural response are available, then the quality of the mesh can be evaluated by methods of comparison. However, in most cases, these are not available. In such scenario, one should be able to evaluate it by refining the mesh until the results get converge to a reasonable value which have low fluctuations.

In line with this approach, the FE model of 5x5 box was configurated with various mesh sizes , such as , lighter to dense . Then the centre span moments for 100 kN Nodal Load, loaded in centre of the deck were compared for each configuration.

The contour diagrams for the critical bending moments, for each mesh configurations, are provided in Figure 27 to Figure 31.

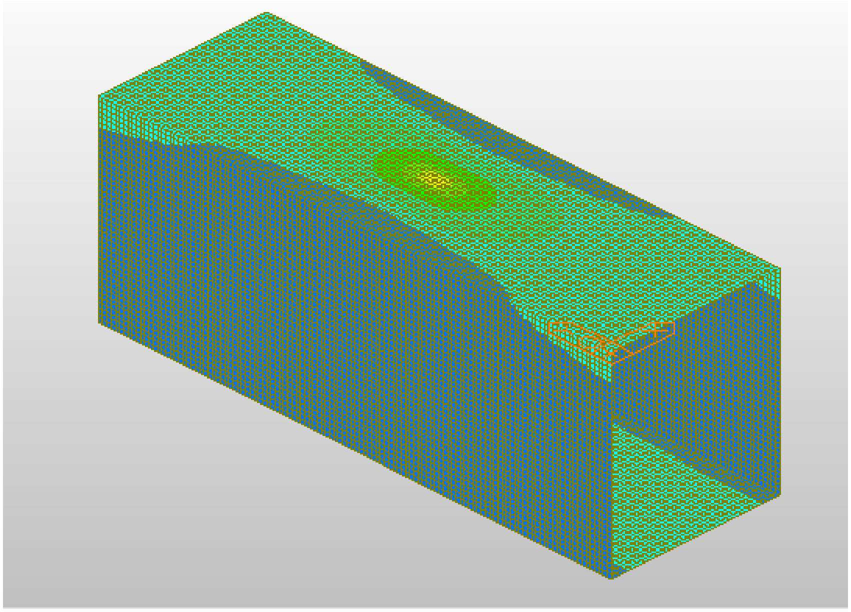


Figure 27 : Mesh Density with 0.125x0.125 m

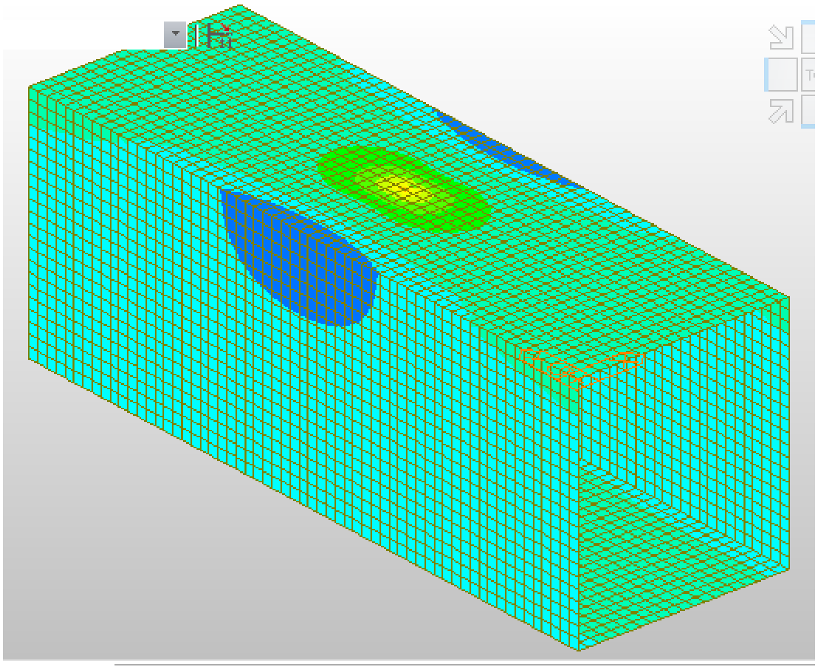


Figure 28 : Mesh Density with 0.25x0.25 m

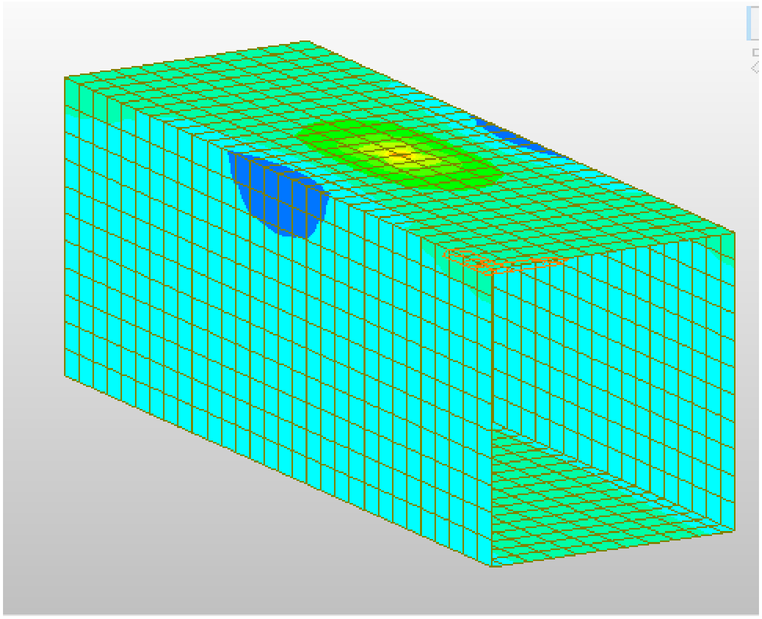


Figure 29 : Mesh Density with 0.5x0.5 m

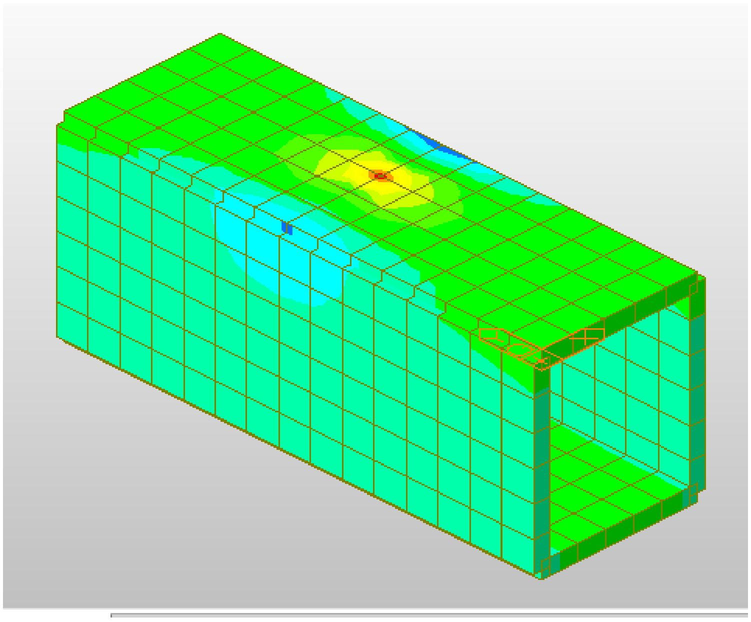


Figure 30 : Mesh Density with 1x1 m

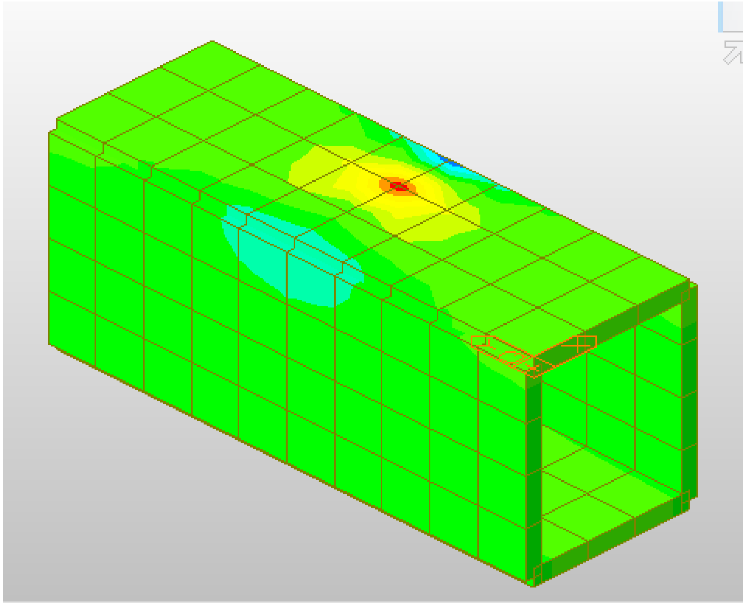


Figure 31 : Mesh Density with 1.6x1.5 m

The result were graphed to identify the convergence of the results and provided in Figure 32.

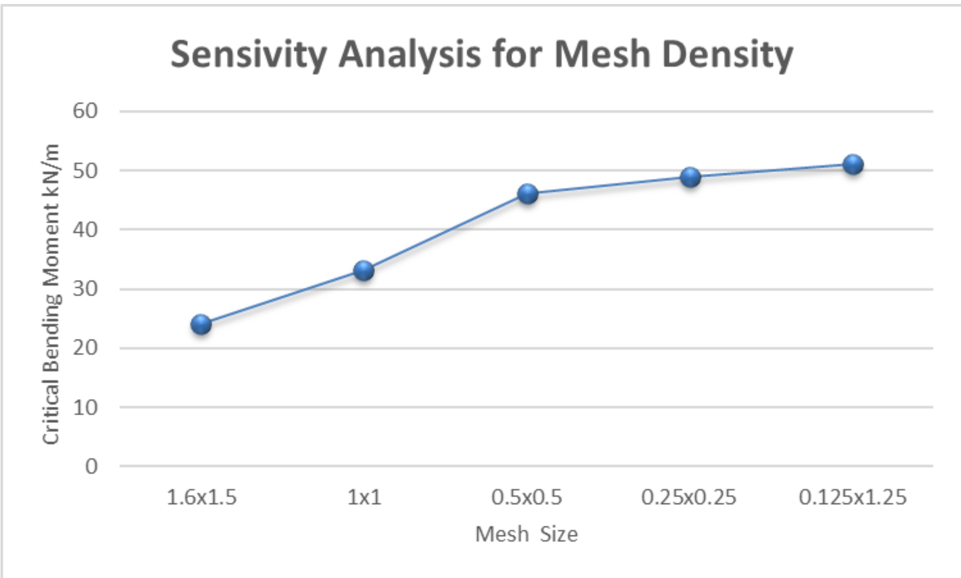


Figure 32 : Critical Bending Moments vs Mesh Density

It can see in Figure 32 that critical bending moment start to converge at 0.5x0.5 m and for finer mesh than of 0.5x0.5 have little improvement of the results.

Considering that, 0.5x0.5m mesh density is sufficiently provide accurate results for 5x5 m box culvert, the same mesh size for lesser spans of box culverts, provides greater accuracy in results.

Thus, 0.5x0.5 mesh density has been incorporated as the optimum solution for all configuration of box culverts in this study.

3.7.3 Critical locations of the model

A study by Feirusha S. H. , 2015 that conducted a 3-dimensional simulation by finite element model has established the status of the principle stress of a box culvert under the following 3 general loads cases (Feirusha,2015) .

1. Structure dead load + Live Loads + Lateral earth pressures owing to back fill
2. Structure dead loads+ Live Loads+ Lateral earth pressure+ inside hydraulic pressure
3. Structure dead loads+ Live loads+ inside hydraulic pressure

The results of this study shows that principle stresses under first load combinations have occurred in the top and bottom slab. The principle stresses under second load combinations have occurred in the bottom slab, while under the third load combination, the principle stresses occurred in corners (Feirusha, 2015).

A drawback of this study is that the live load traffic has been simulated as a uniformly distributed load ignoring the concentrated wheel loads, which are obligatory to consider in both BS 5400 and Eurocode.

In a different study on the design of a box culvert using finite element methods (Tikate & S.N Tande, 2015) the centre span of the top & bottom slab and the corners have been considered as the most critical locations for structural design.

In line with above research findings, this study adopted a comparison of mid span moment of the deck slabs to compare the effects of traffic loads that induced and defined by BS & Eurocode.

3.8. The Soil Parameters

3.8.1 Formation of the Structure

Kansas Department of Transportation (KDOT), US, has recommended conducting a frame analysis to ansyse the box culverts. They propose a more realistic method for boundary conditions where they specify linear translational springs based on the Modulus of Subgrade to simulate the flexible foundation and wall /earth interface as shown in Figure 33 (KDOT, 2007).

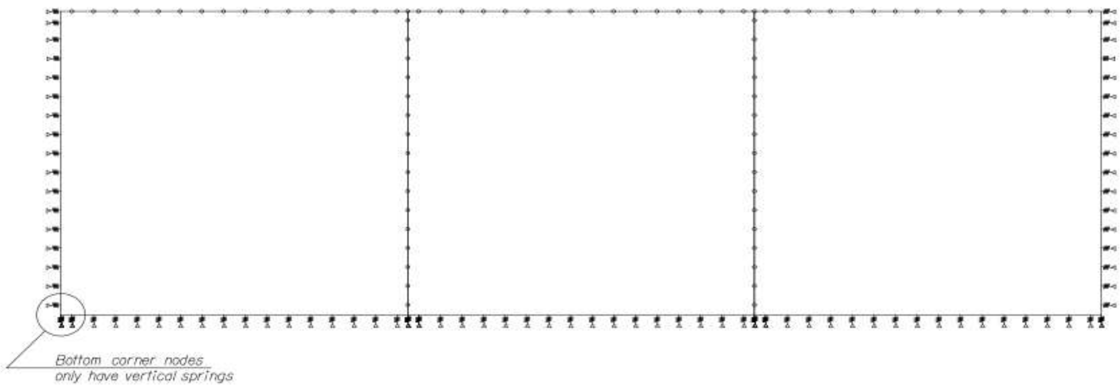


Figure 33 : Frame Analysis with Springs

Source : (KDOT, 2007)

Though two dimensional FE models would be sufficient, this study has adopted , state of the art, three dimensional FE models for comparison of traffic loads. By creating three dimensional models , the traffic load dispersion effects are possible to analyse accurately.

3.8.2 Earth Cover

Depending on the designed road profile, the box culverts are placed either the top slab is almost at road level or below the road level. The gap between road level and culvert top is filled with soil or pavement material. In such instances, the soil cover acts as a cushion, and the height of the cushion shall be varied as per the road profile and culvert invert level (Tikate and S.N.Tande, 2015).

The effect of surface vehicle loads, generally referred to as live loads, are most significant when the soil cover that rests on the deck slab is thinner. As the soil cover increases, the effect of live loads get decreases (Ahmed, 2006). Having identified this phenomena, the DMRB guideline recommends the direct application of vehicle loads without dispersion for soil cover less than 600mm (DMRB, 2001)

A similar conclusion has been arrived at by the studies of Tikate and S.N Tande, who have conducted an analytical research on the effect of soil cushion to design output. In his studies, varying thicknesses of cushion from 0 to 5m deep with 1m interval have been compared, and it has shown that in the cases of thicker cushions, the live load get dispersed in a larger area through the fill and effect of the live loads get insignificant. Hence as a conservative approach, they recommend designing the box culvert with zero thickness of soil cover (Tikate and S.N.Tande, 2015).

In conjunction with DMRB practice, the dispersion of the concentrated vertical load is differentiated with the thickness of the fill. Should the fill be lesser than 0.6m, the dispersion of load is ignored. As such, HA and associated KEL or appropriate HB is directly applied to the slab of the box culvert. In the cases where fill is greater than 0.6m, HA and associated KEL is ignored, but appropriate units of HB is applied with a load dispersion of 1:2 (Horizontal : Vertical) through the thickness of the fill (section 3.2DMRB, 2001).

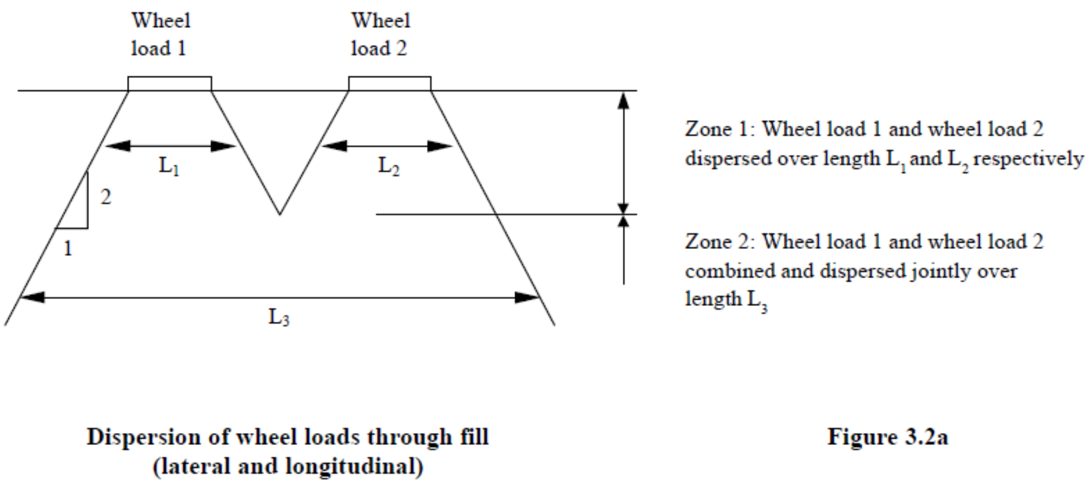
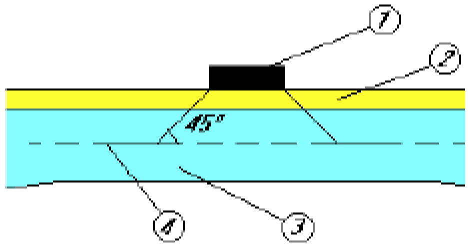


Figure 34 : Recommended Load Distribution for BS

In Eurocodes, it recommends converting the tandem loads into an equivalent uniformly distributed load, probably in an area of 3m wide and 2.2m long, and apply a dispersion angle of 30 degrees. Further, it recommends searching for better dispersion guideline in EN 1997, the Geotechnical Design of Eurocode (BSI, 2003).

As for this study, in view of maximising the effects owing to traffic loads, no earth fill is considered. Thus, method of dispersion through the earth fill is not significant and not applicable for this study.

Both DMRB and Eurocode specify 45 degrees of dispersion through the roof slab as shown in Figure 35 (BSI, 2003, DMRB, 2001). In addition to roof slab, the same dispersion rule is adopted for pavement as specified by the cl 4.3.6 of EN 1991.2.



Key
1 Wheel contact pressure
2 Pavement
3 Concrete slab
4 Middle surface of concrete slab

Figure 4.4 - Dispersal of concentrated loads through pavement and a concrete slab

Figure 35 : Recommended Load Distribution for EC

(BSI, 2003)

The objective of this research is to identify the effect of traffic loads on the box structures. Hence, in view of maximizing the effects of vehicle loads, zero thickness of soil cover is taken into analysis with provision for a 50mm thick asphalt wearing course.

A similar approach has been adopted by K.Garg and Abolmaali in their study of shear capacity of the precast box culverts where the worst case was identified as without cushion owing to diminishing effect of wheel loads (K.Garg and Abolmaali, 2009).

3.8.3 Lateral earth pressure

The static earth loads were applied to relevant parts of the FE model, and the horizontal earth and surcharge pressures were applied to the sidewall of the box culverts.

The lateral earth pressure causing a negative moment in the mid span of the top and bottom slabs, as shown in Figure 36 . Thereby relieving the span moments of each components. However as described, in section 3.7.2 , mid span moment are taken in to the comparison of various box configuration and relevant traffic loading. Since lateral earth pressure will create negative effects, the span moment would be compromised.

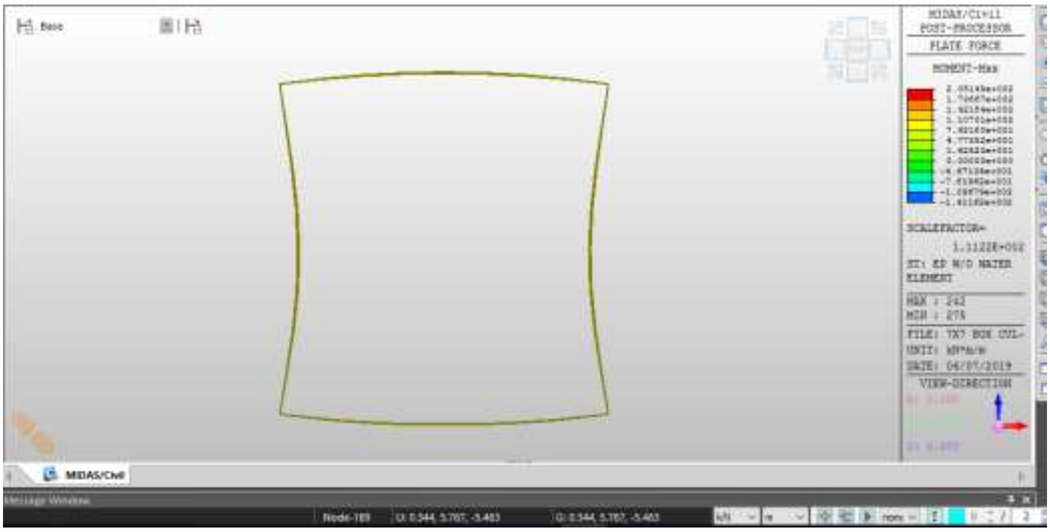


Figure 36 : Lateral Earth Pressure on Box Structure causing Hogging in Top Slab

Thus, as specified by both codes of practice, the reliving effect of the lateral earth pressure on relevant structural elements are appropriately considered in the combination of actions.

Further, both codes of practices adopt lateral earth pressures as a permanent or persistent load The relevant combination factors are adopted.

3.9 Temperature Effects

The temperature effects such as mean temperature and temperature gradient were assigned to the FE models.

However, as shown in Figure 37 & Figure 38, the variation of mean temperature to box structure cause zero effects on roof slab.

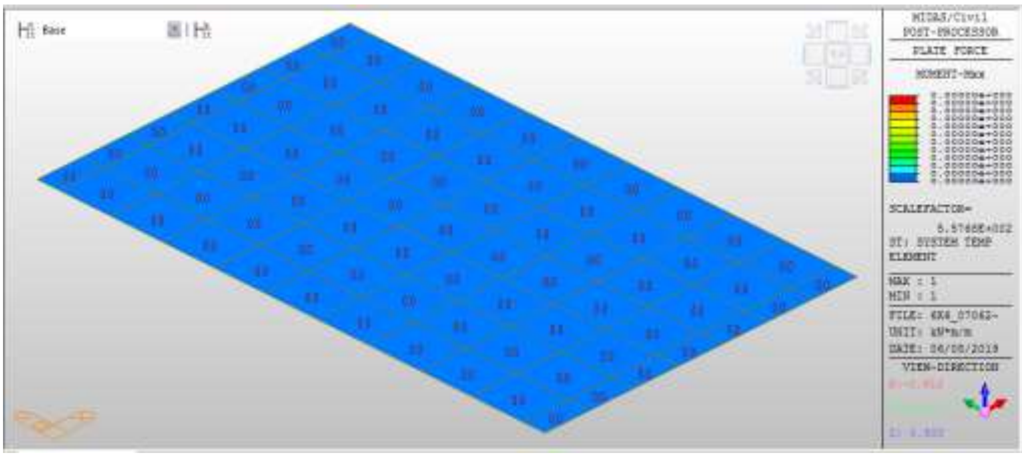


Figure 37 : Zero Effects on Roof Slab BM owing to Positive Mean Temperature Variations

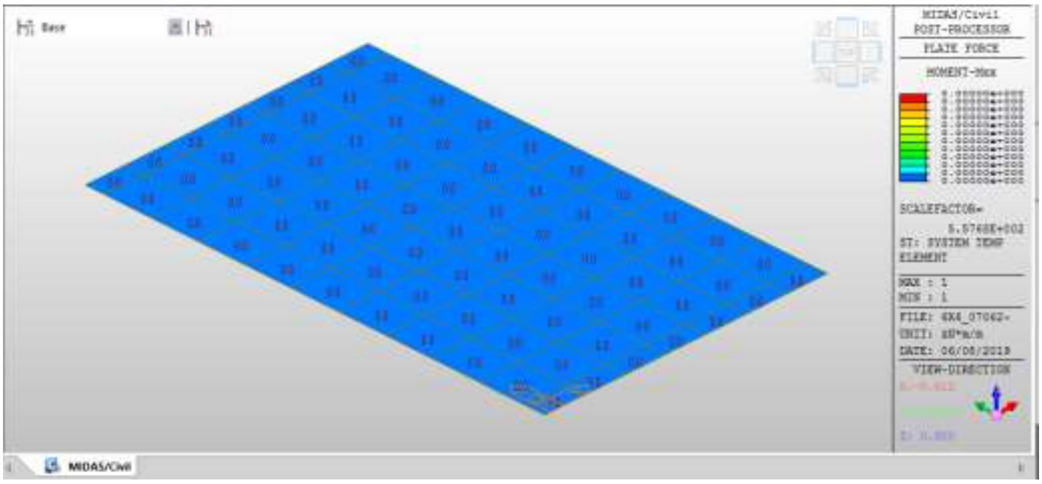


Figure 38 :Zero Effect on Roof Slab BM Owing to Negative Mean Temperature Variations

3.9.1.Differential Temperature

This is applicable only to the roof slab.

When considering the temperature effects on top slab, the positive gradient of differential temperature is considered as it provides the most critical values.

Owing to the positive deferential temperature, the top slab is moving upwards and inducing a sagging moment at the span of the top slab as shown in Figure 39.

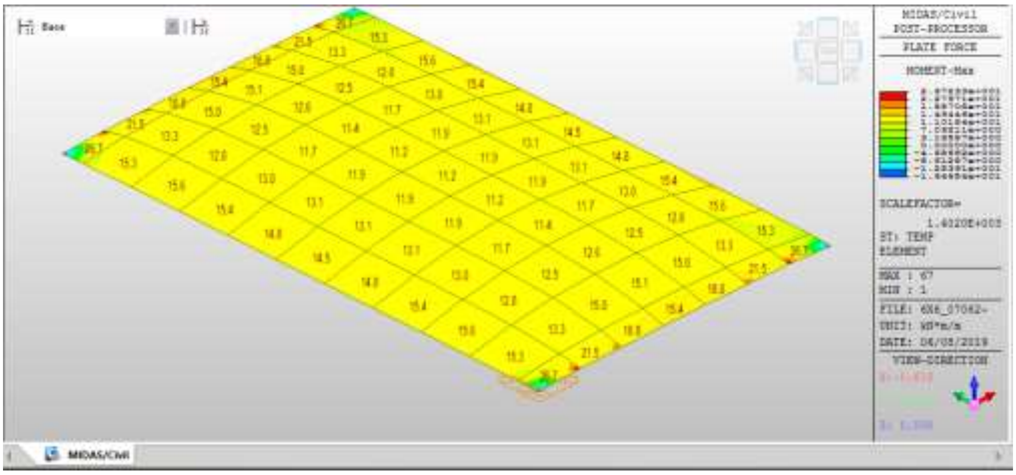


Figure 39 : The Critical Effects in Span Moment (Roof Slab) owing to Positive Temperature Gradient Inducing Sagging Moment at Mid Span

Owing to the negative deferential temperature, the top slab is moving downwards and inducing a positive moment at the span of the top slab as shown in Figure 40.

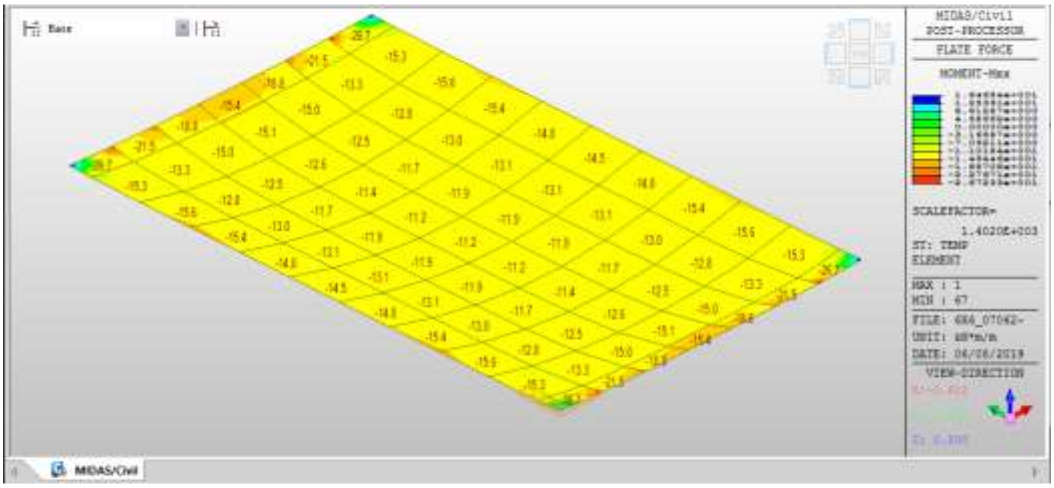


Figure 40 . The Reliving Effects on Top Slab Span Moment Owing to Negative Gradient of the Differential Temperature Inducing Hogging Moment at Centre.

The negative deferential temperature, create global deformations shown in Figure 41.

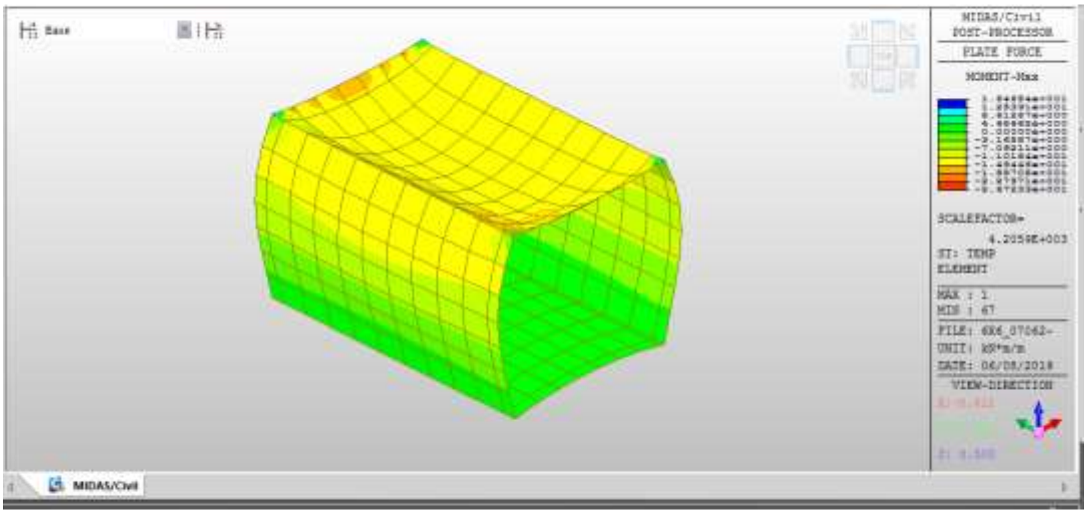


Figure 41 : Deformation of Structure Owing to the Negative Gradient of the Structure.

The positive deferential temperature, create global deformations shown in Figure 42.

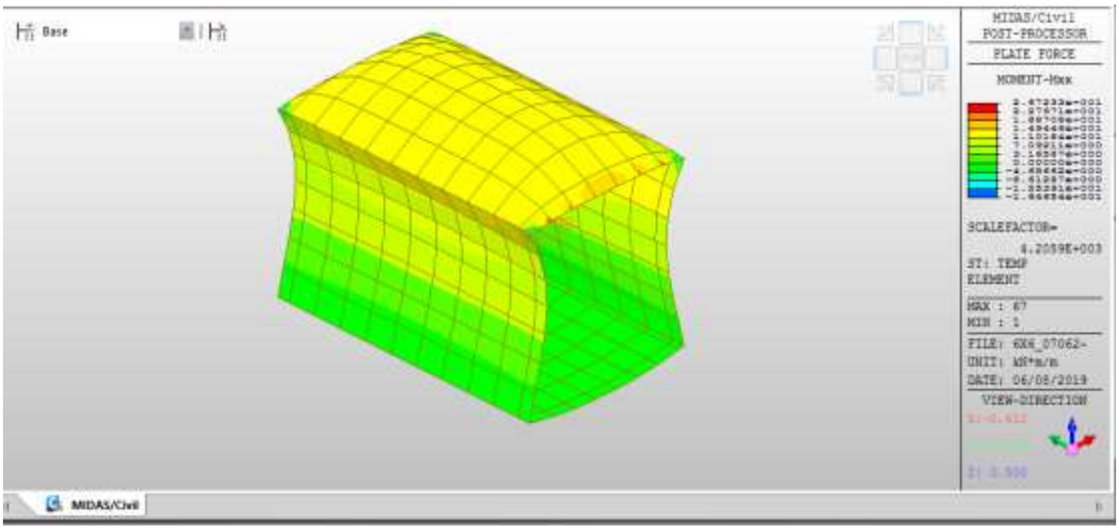


Figure 42 : Deformation of the Structure Owing to the Positive Gradient of the Structure

With this analysis, it is clear that positive differential temperature provide the critical effects in structural behaviour of the box and when computing the load combinations relevant values of positive gradient of temperature is taken in to account.

3.10 Case Study – 3x3 Box Structure

<u>Details of the model – a case study for 3x3 box Culvert</u>

3m x3m box culvert was modelled using 4 node plate element as shown in Figure 43 and Figure 44. The thickness of the plate was taken as 0.3m to accommodate the serviceability requirements and to optimise the deflections.

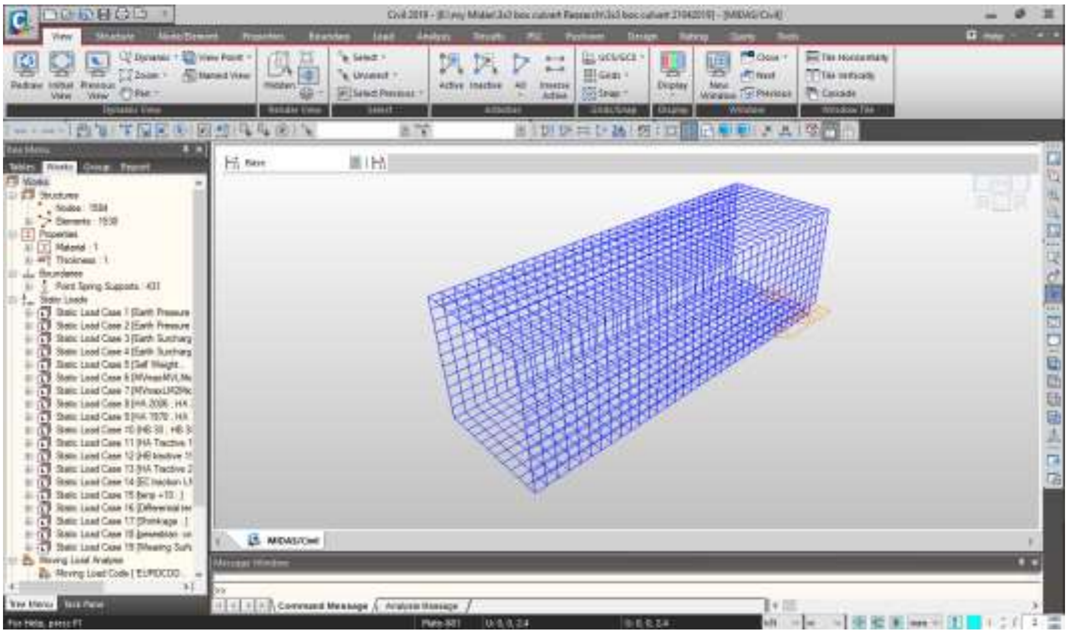


Figure 43 : Wire Mesh image of Finite Element Model for 3x3 Box Structure using MIDAS Civil

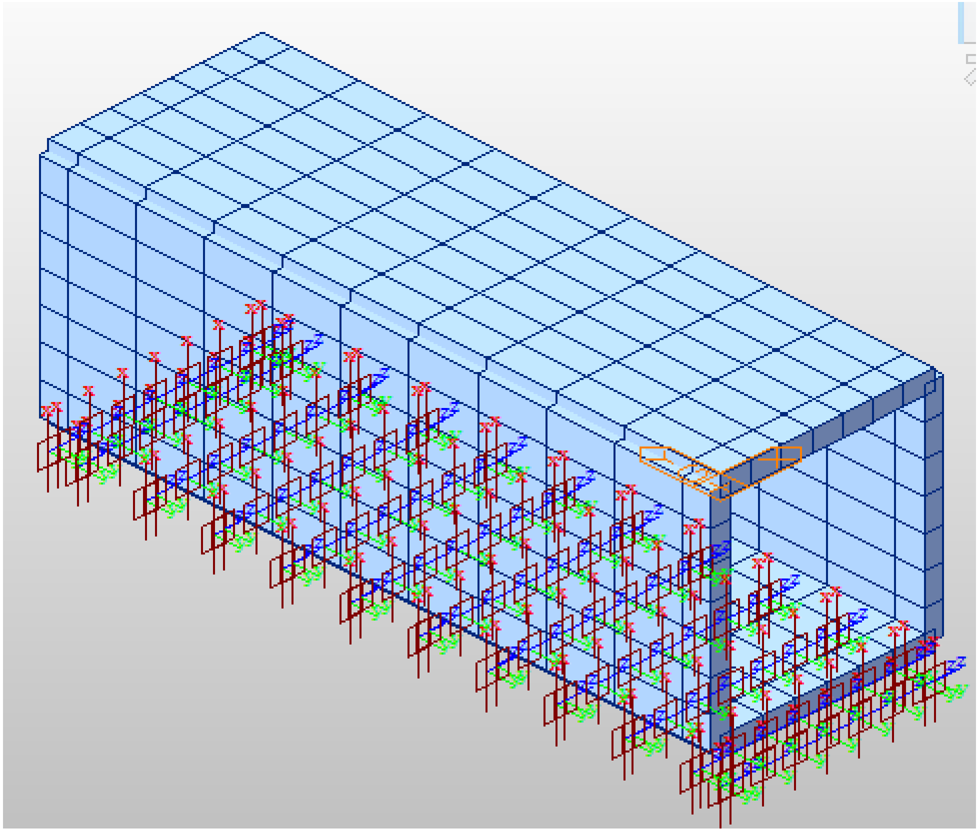


Figure 44 : 3D Model

The boundary conditions of the box culvert, which rests on soil were simulated with elastic links connected to point spring support shown in Figure 45. The stiffnesses of the elastic links were determined by soil subgrade modulus based on the 150 kN/m^2 of allowable bearing pressure in ground. Assuming that 25mm elastic settlement is safely withstand by the structure. The elasticity of the elastic link was determined by 150 kN/m^2 / 0.025 m = 6000 kN/m^3. By introducing a safety factor of 3 for allowable bearing pressure , the adopted elasticity for the links is computed as 18000 kN/m^3 in vertical directions.

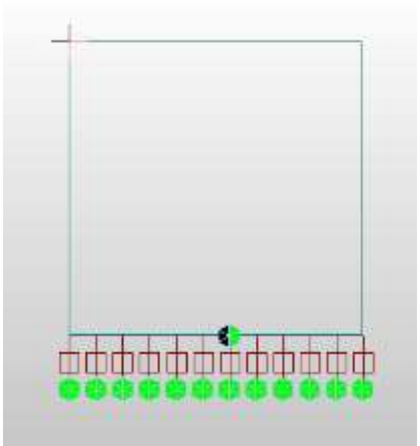


Figure 45 : Boundary Conditions applied to the Box Structure

The static loads were applied to relevant parts of the structure.

The horizontal earth and surcharge pressures were applied to the side wall of the box culvert as shown in the Figure 46 and Figure 47. Here assuming that drain conditions are prevailing , the active earth were applied to the side walls incorporating lateral earth co efficient , k, as 0.3.

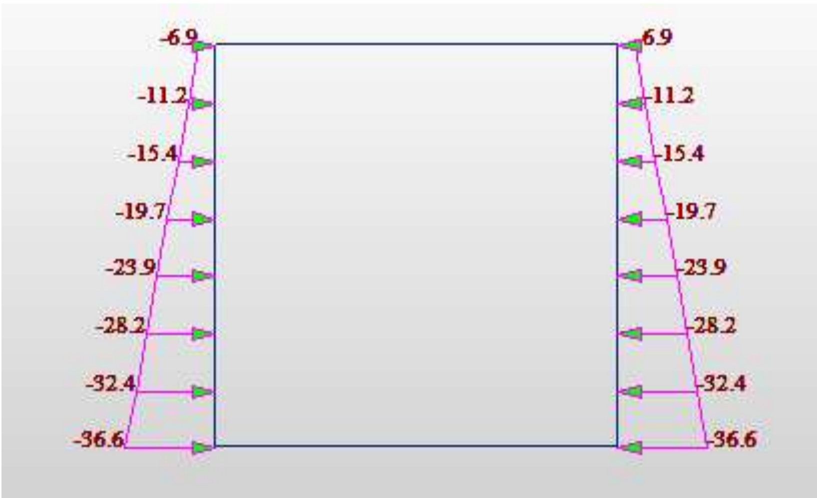


Figure 46 : Lateral Earth Pressure applied 2D

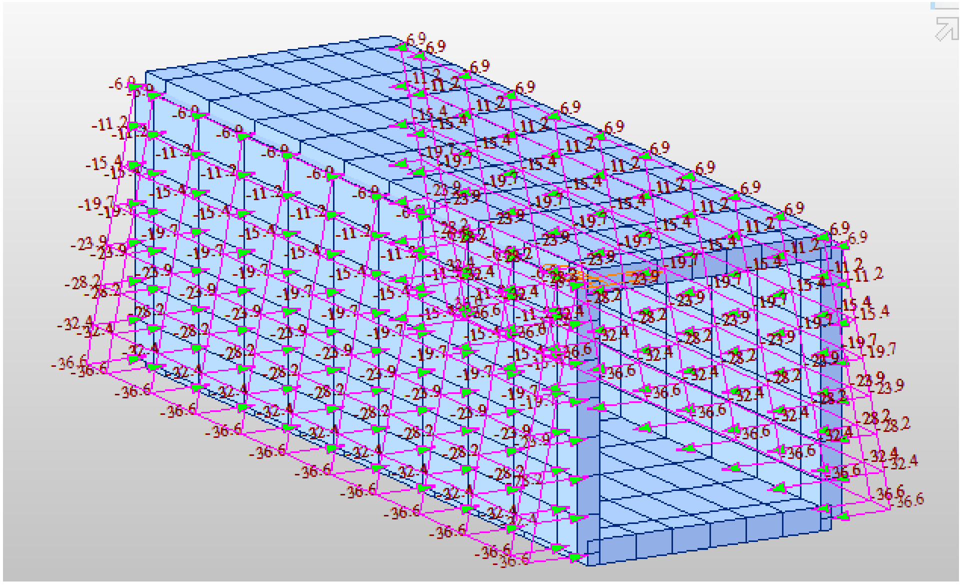


Figure 47 : Lateral Earth Pressure in 3D

The traffic Loads of the BS 5400 (2), were applied as static loads, and KEL was positioned to provide the maximum structural effects considering the positive influence lines. The Figure 48 is depicting the HA UDL load applied in relevant notional lanes.

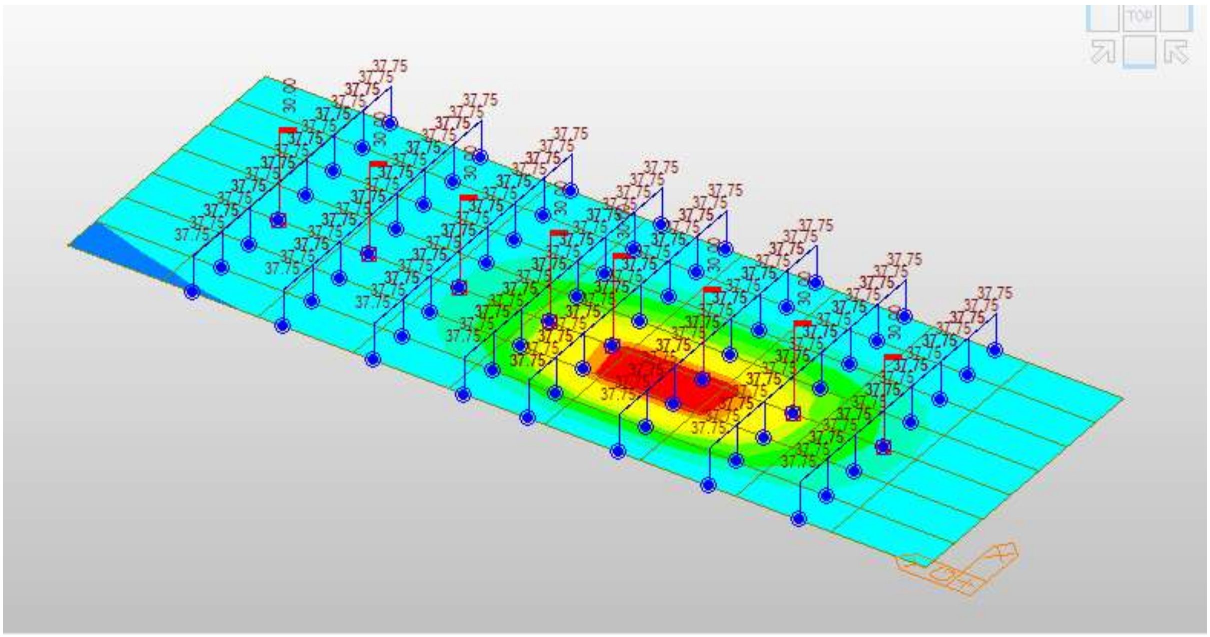


Figure 48 : HA UDL Applied in top Slab to provide critical effects

In view of introducing Eurocode moving loads to the structure, the notional lanes were defined as shown in the Figure 49 & Figure 50. The lanes were defined and allocated as described in section 3.6. Since width of the carriageway has been taken as 7.4 m the number of notional lanes would be 7.4/2 = 2 notional lanes. The remaining area would be 7.4 -2x3 =1.4 m

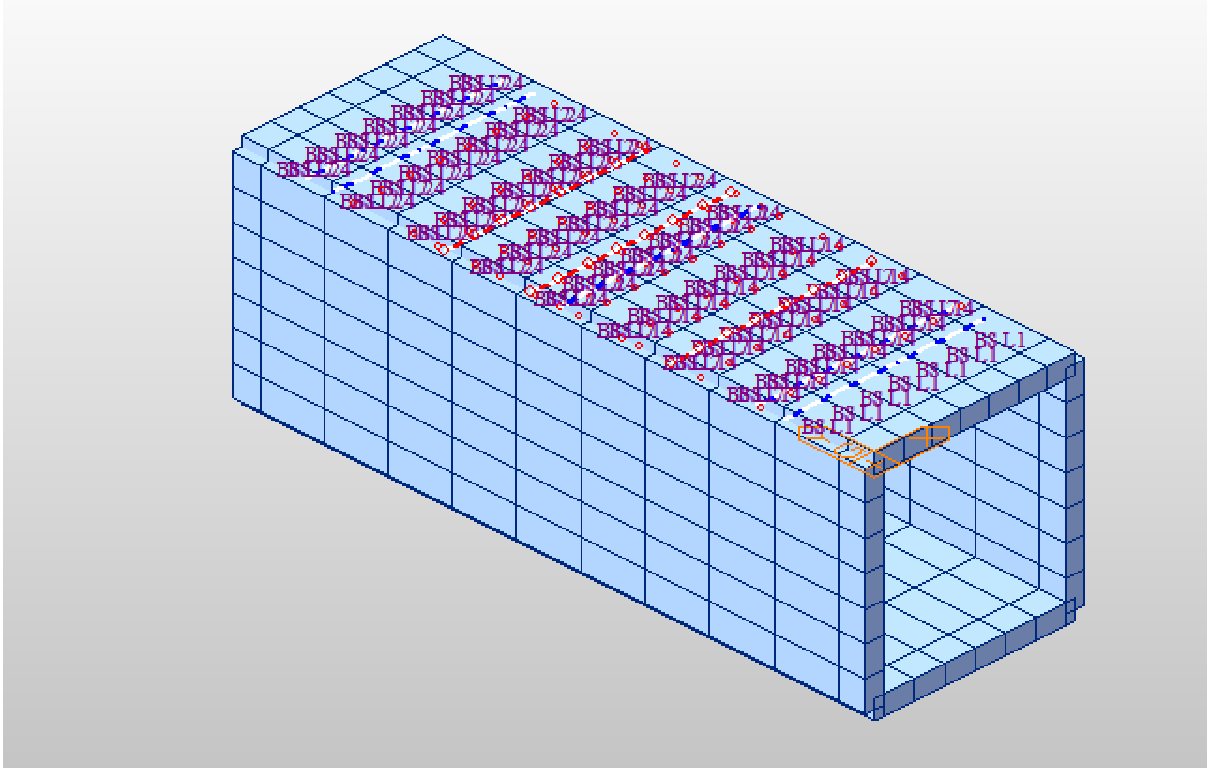


Figure 49 : Lane Definition for Eurocode

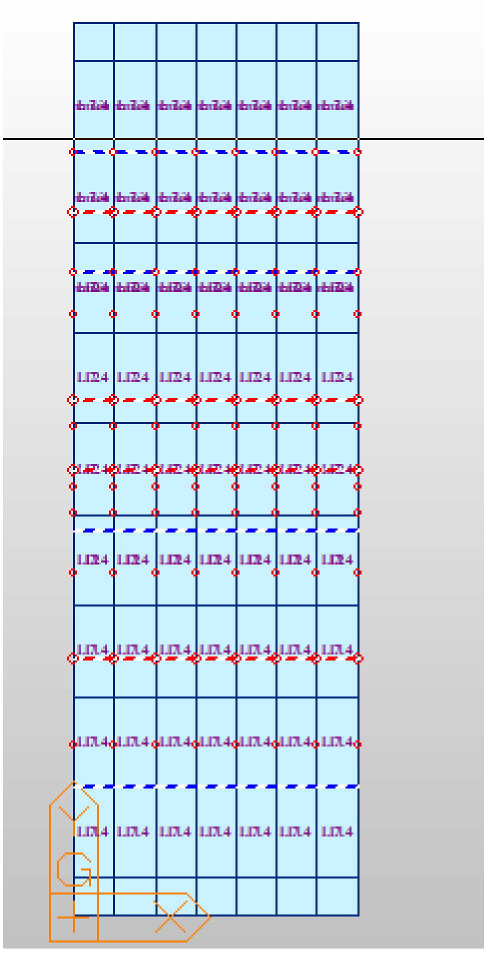


Figure 50 : Lane Definition plan View

Once the lanes were defined, the Load Model 1, the load was applied in conjunction with Eurocode as show in Figure 51.The Eurocode traffic model, Load Model 2 (LM2) was defined as Figure 52 and applied the same as a moving load to the each FE model.

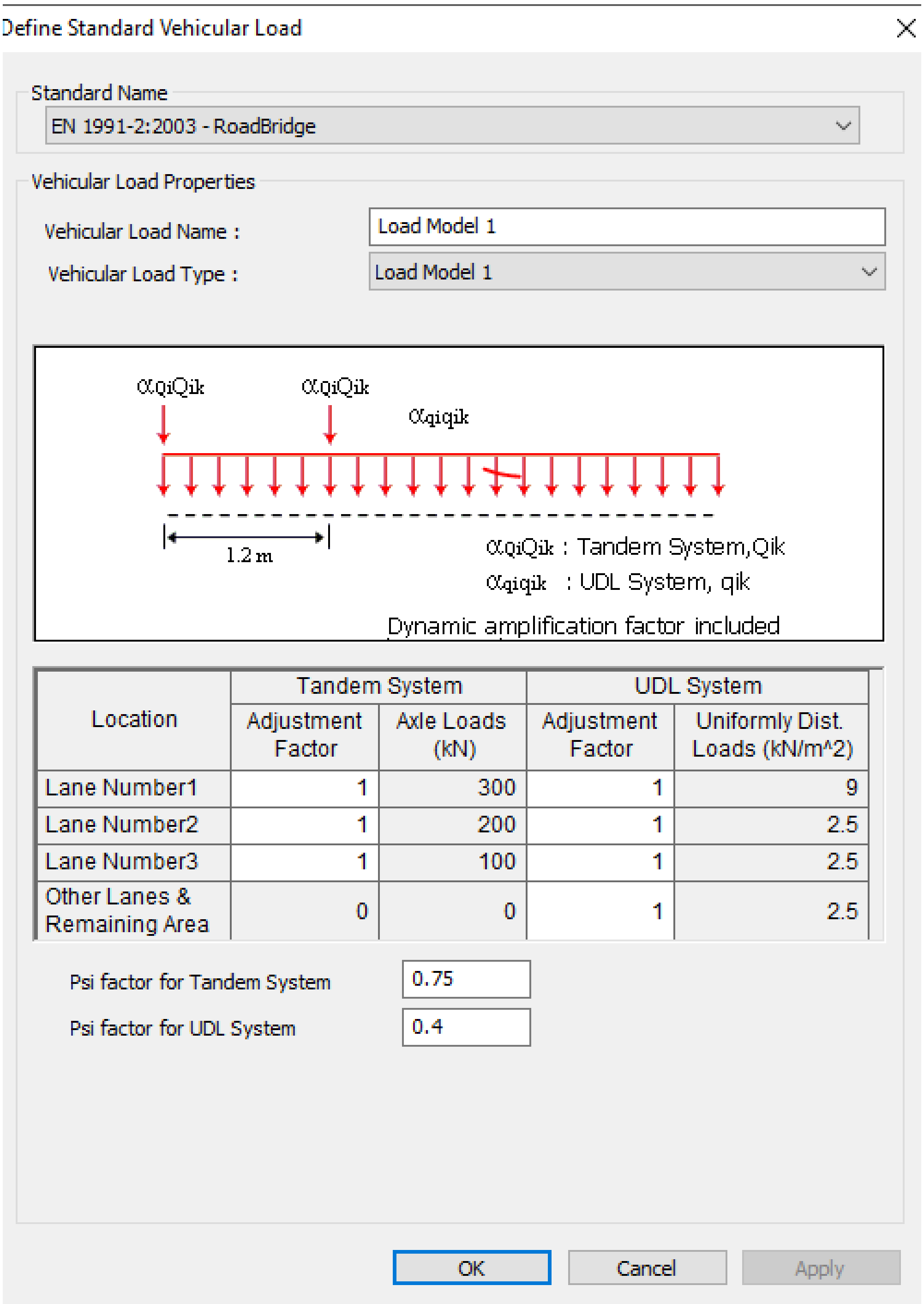


Figure 51 : Load Model 1 defined in MIDAS Civil

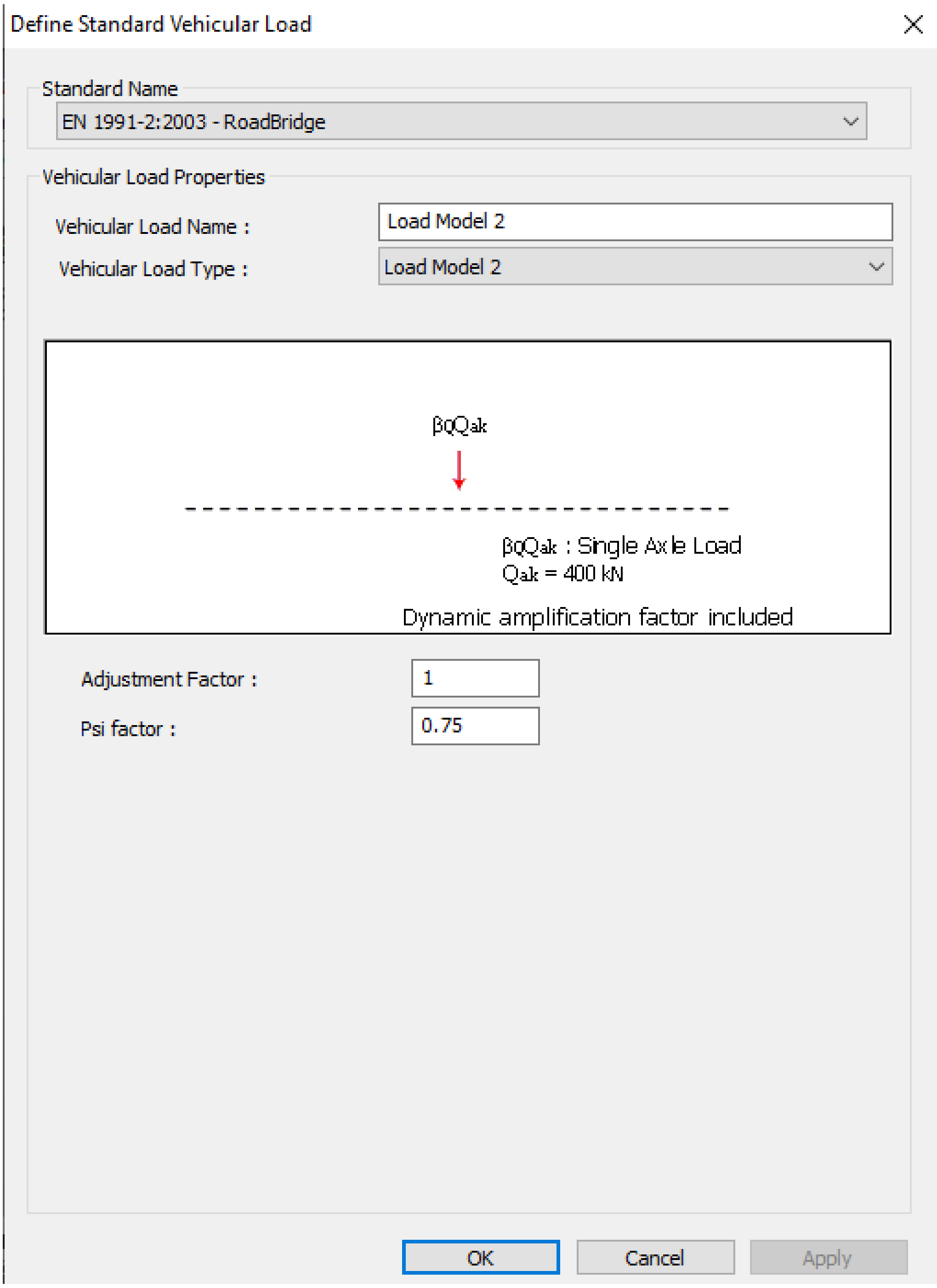


Figure 52 : Load Model 2 defined in MIDAS Civil

As earlier discussed in section 3.2.2, SV 80 is selected as the Load Model 3 (LM3) for this study. Figure 53 shows the definition of LM3 and same is incorporated to the FE Model.

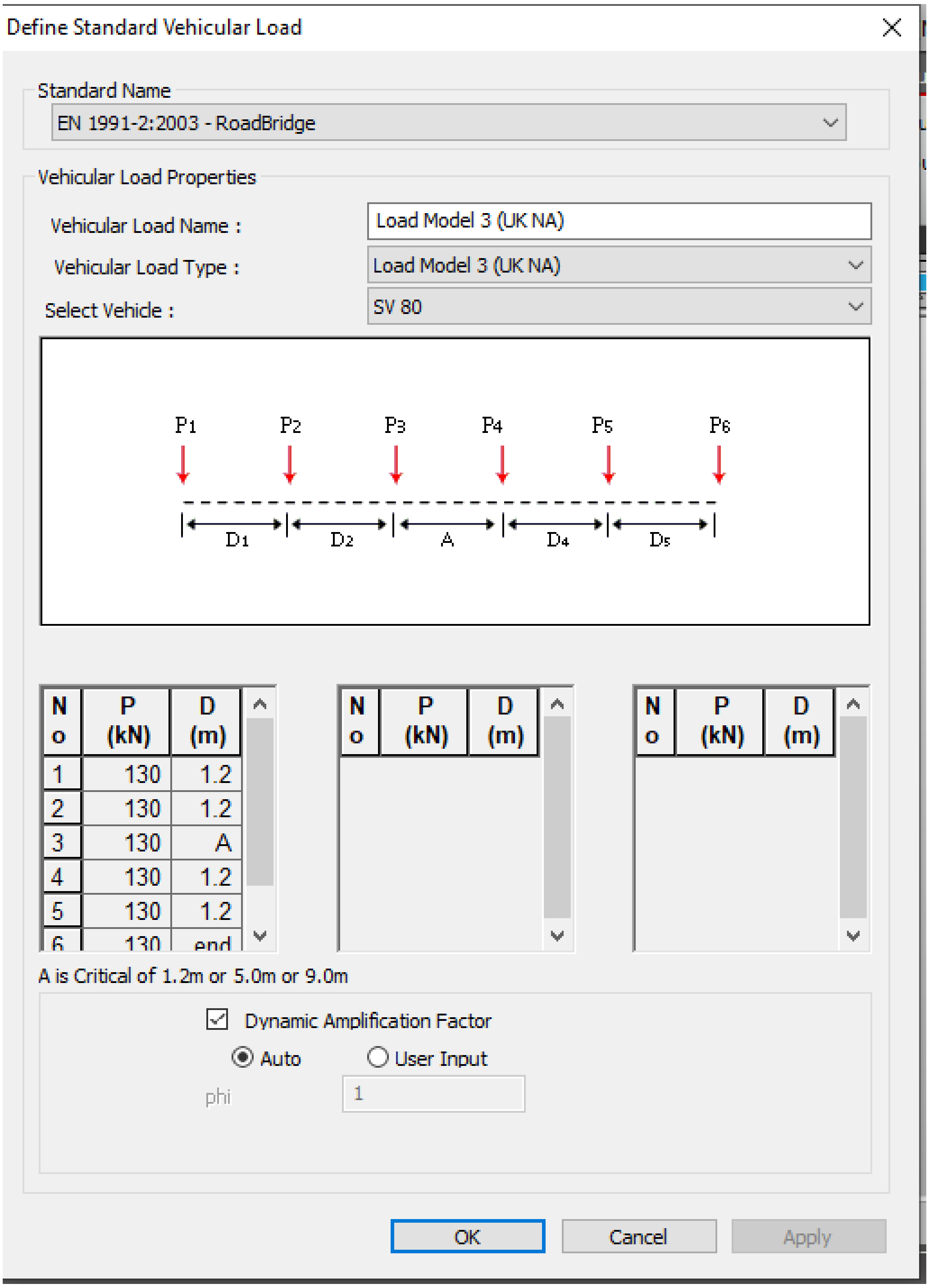


Figure 53 : Load Model 3 defined in Midas Civil

In conjunction with load combinations defined in section 3.5 , similar combinations were defined in the FE models, The Figure 46 shows various combinations adopted in this particular box culvert.

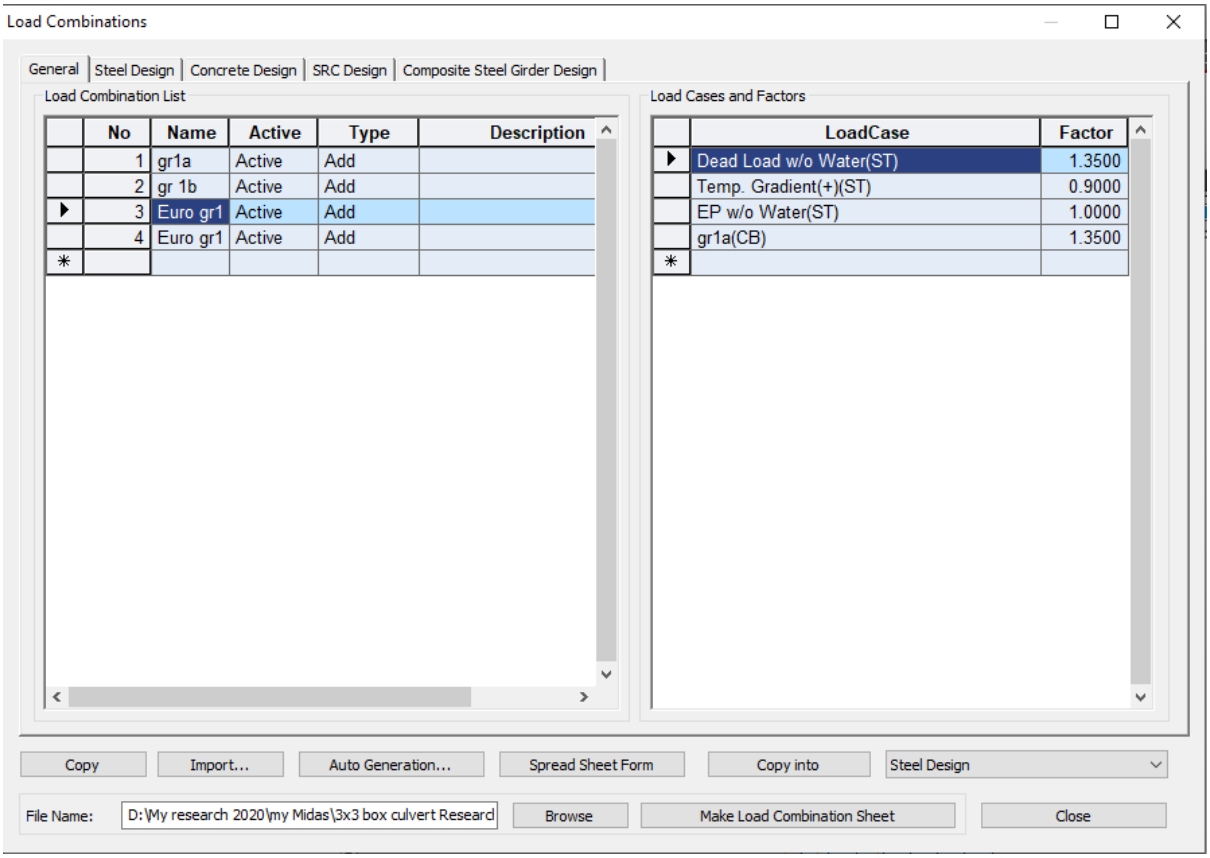


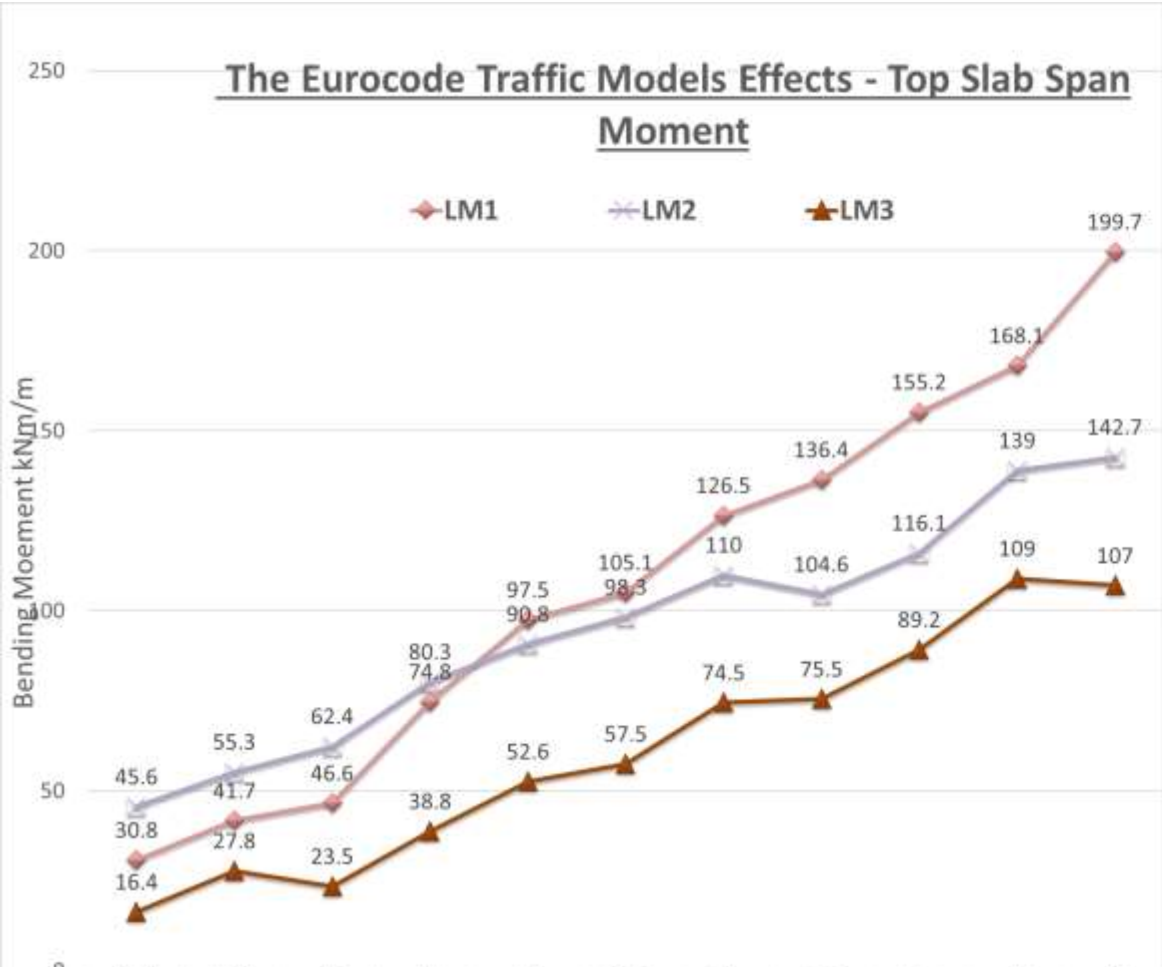
Figure 54 : Load Combination defined in MIDAS Civil

4.0 Results of the Analysis

4.1 Results from Eurocode Traffic Model

4.1.1 Critical Load Models of Eurocode

The span moments of the top slab were examined, in conjunction with section 3.7.2. of this thesis, to establish the critical traffic load model. The results for different load model in Eurocode are shown in Figure 58.



	1.0 x 1.0	1.5x1.5	2x2	3x3	4x4	4.5x4.5	5x5	5.5 x5.5	6x6	7x7	8x8
LM1	30.8	41.7	46.6	74.8	97.5	105.1	126.5	136.4	155.2	168.1	199.7
LM2	45.6	55.3	62.4	80.3	90.8	98.3	110	104.6	116.1	139	142.7
LM3	16.4	27.8	23.5	38.8	52.6	57.5	74.5	75.5	89.2	109	107

Figure 58 : Comparison of Eurocode Traffic Load Model Effects

It is clear that either LM1 or LM2 provide the most critical effects but not LM3 , for these box configurations.

The structural effects provided by the LM2 are critical for shorter spans up to the configuration of 3x3 box culverts. For greater spans than of 3x3, i.e. box culverts confutation of 4x4 to 8x8, the LM 1 provide more severe structural effects than LM 2 and LM 3. This phenomenon is in line with the specifications of BS -EN 1991 -2, as LM 2 has been introduced to cover the dynamic effects of the normal traffic on short structural members.

In this distribution depicted in Figure 47, two regions on can be identified where in first region it is comprised of smaller spans of box configurations and Load Model 2 is providing the critical effects. The second region includes the higher spans of box configurations, and Load Model 1 provides the critical effects.

Figure 59 shows the general mid span sagging ULS bending moment contours, resulted from the load envelop of Eurocode loading for box configuration of 5mx5m.

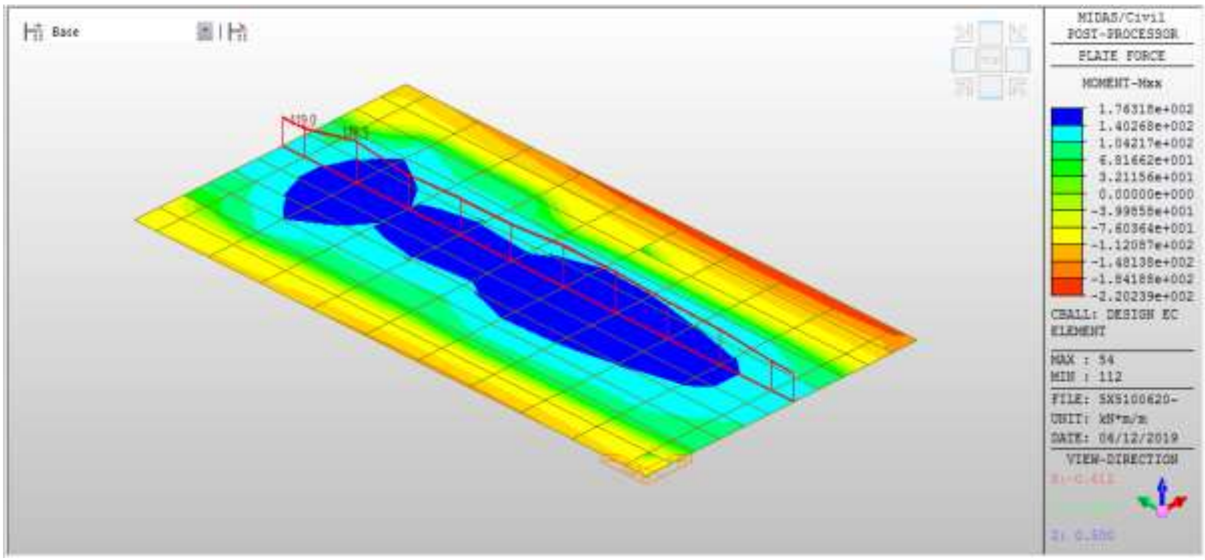


Figure 59 : Typical Critical Span Moments Contour Diagram (top slab)- Shorter Span Box Culvert (5x5)

Since bending moment contour envelop given by Figure 48 is a combination of results originated from various load models , the exact critical moving load placement can be extracted from the FE model. The Figure 60 is shown the such a critical load placement for Load Model 2 , for 5mx5m box culvert configuration.

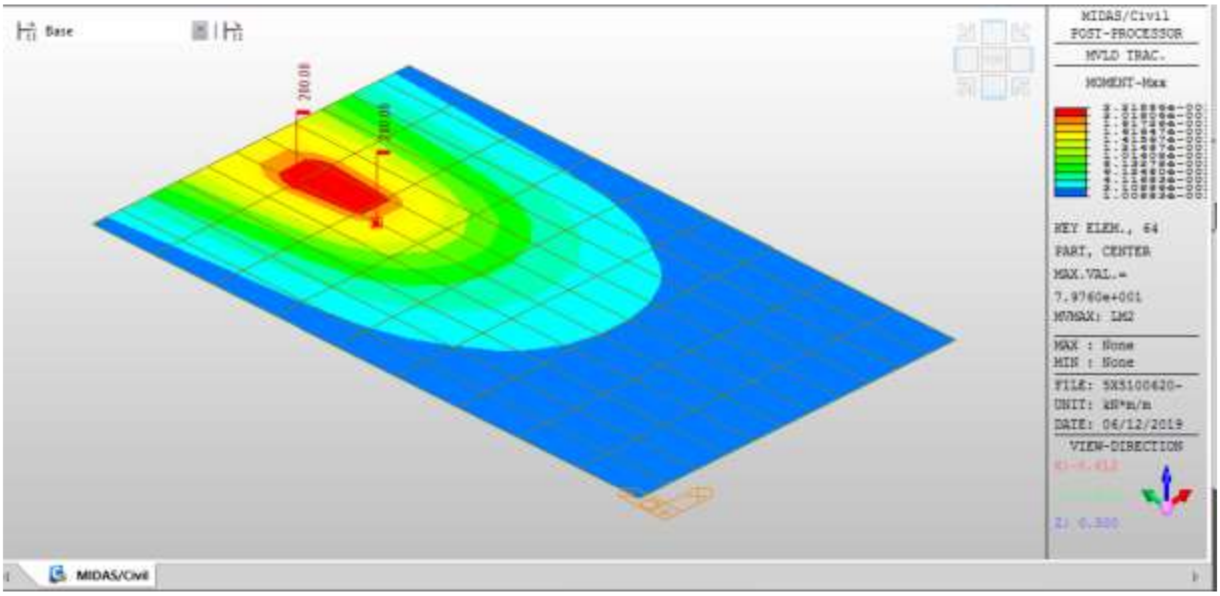


Figure 60 : Critical Load Arrangement for Critical Span Moment for top Slab of Shorter Span Box Culvert LM 2-Load Model (5x5)

Similarly, critical load placement for Load Model 2 and Load Model 3 can be extracted from FE model in respect critical mid span moment or other structural effects.

4.1.2. Critical Load Combinations of the Eurocode

As discussed in section 3.3 of this thesis, when combining permanent and variable actions in Eurocode, the traffic models are to be considered as a group which is given in Table 6 in section 3.3 of this thesis. Here gr 1a consists with characteristic load effects of LM1 and the gr1b consist with characteristic load effects of LM2.

The critical span moments for each box configuration and critical combinations of actions are given by Figure 61 below. In Figure 61, the blue line represents the ULS combination of actions where gr 1a is the leading variable. The red line denotes the ULS combination of actions where gr 1b acts as the leading variable. Since LM3 is not critical for any of the configuration of box culverts, the combination of actions owing LM3 as a leading variable is not accounted for comparison.

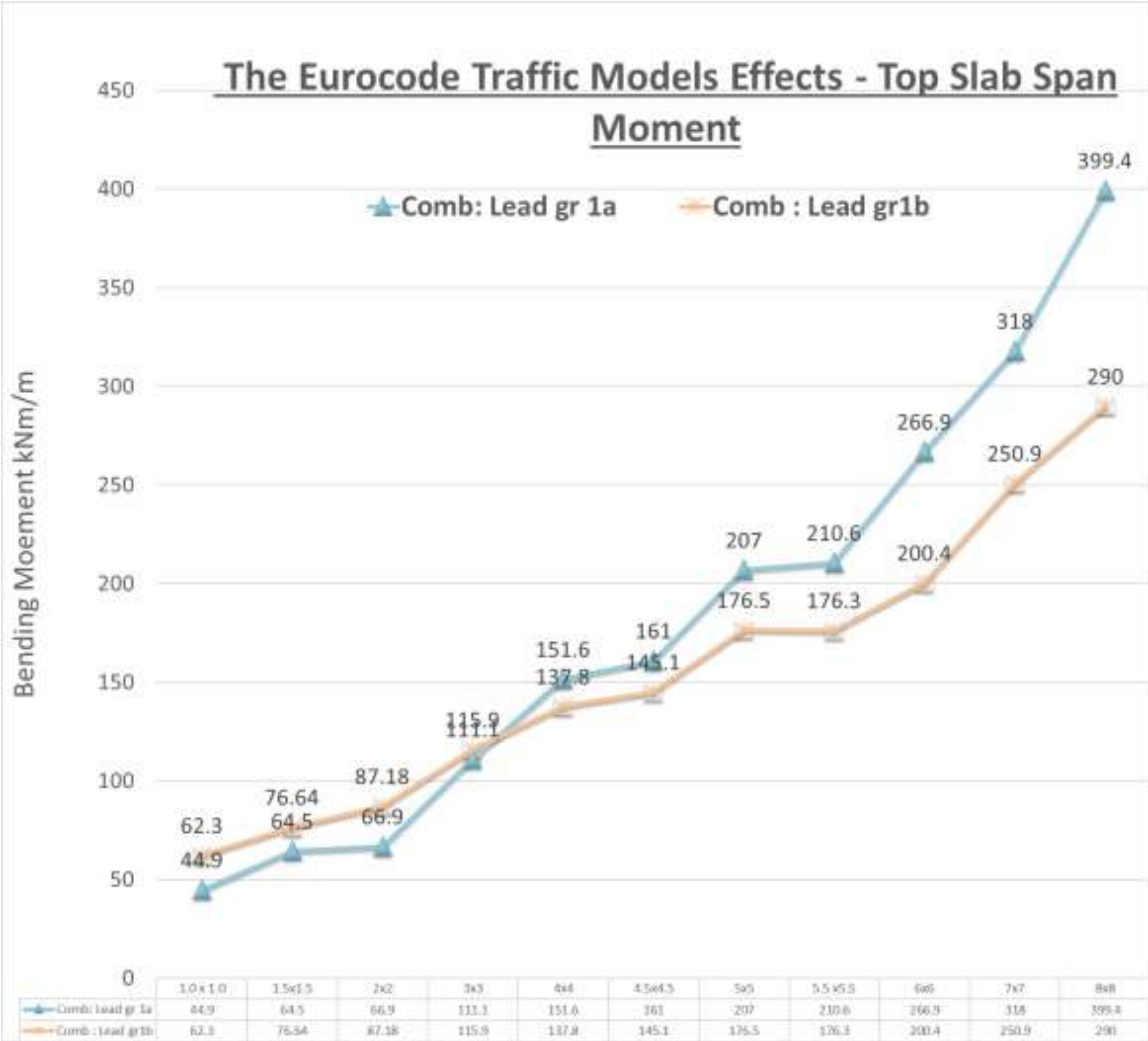


Figure 61 : :Comparison of EC Critical Traffic Load Combinations

The result provided by the ULS combinations in Figure 50 have a similar pattern described in section 4.1.1. i.e for box sections where span is lesser than 3x3, the gr 1b (LM2 related) is critical while for grater span of 3x3 , the gr 1a (LM1 related) is critical. Even though, temperature actions are incorporated in the combination of actions, same pattern that observed in the LM1 & LM2 is projected to the combinations as well. This is significant, because temperature actions are increasing the span moments, as described in section 3.9 , and temperature effects are considered along with LM1 only , as described in section 3.3.

4.2 Results from BS traffic Loads

Similarly, BS traffic loads effects on top slab span moments, in conjunction with section 3.7.2, were examined and results are shown in Figure 51. As described in section 1.3, different versions of BS 5400 given below , and its traffic models are accounted in the comparison.

1. Part 2: BS 5400: Specifications for Loads published in 1978.
2. Part 2: BS 5400: Specification for Loads published in 2006

In Figure 62, the blue line represent the HA load effects in conjunction with BS 5400 (2006) version and named as HA 2006 for simplicity. The green line represent the HA load effects owing to BS 5400 (1978) version and marked as HA 1978. Since there is no difference for HB in both 1978 and 2006 version, the single red line depicts the load effects for HB and marked as HB 30.

The HA 2006 loads are critical than HA 1978, and this is owing to the higher intensity of uniformly distributed loads given in the 2006 version as described in . In the cases of the loaded length of 2m to 8m, the UDL of HA 2006 is varying from 211.2 kN/m per notional Lane to 83.4 kN/m per notional lane. In HA 1978 version, this UDL consistently remains as 30kN/m for the notional lane. However, HB 30 provides critical traffic condition in the BS 1978 version, while in the 2006 version, HA 2006 provides the critical loads other than the box configuration of 1m x 1m.

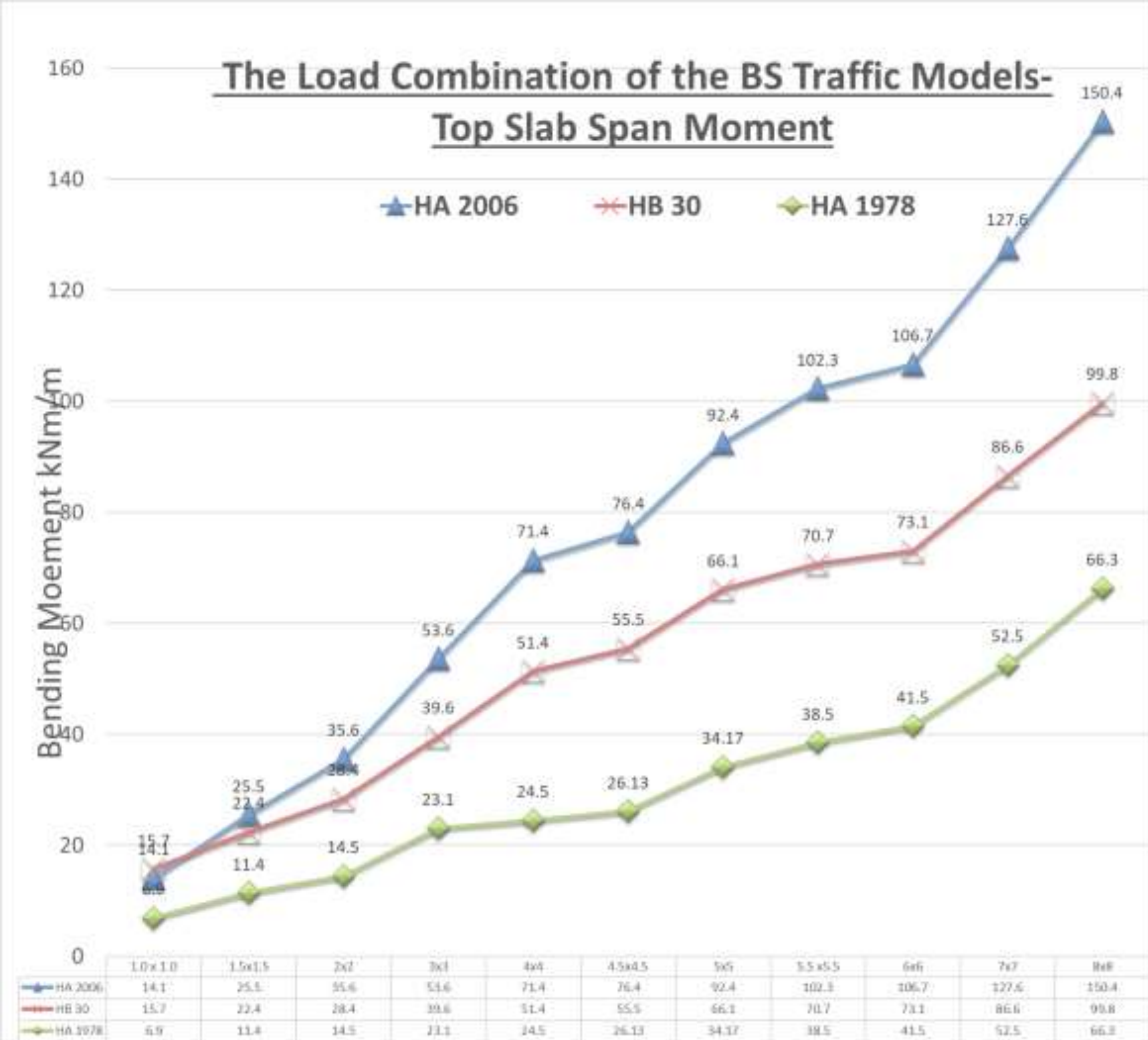


Figure 61 :Comparison of BS Traffic Loads

4.3 Comparison of the results of different code of practice

Once the critical traffic load cases were compared within the each code of practices, the critical design moments of BS & EC, selected from the relevant bending moment envelops, are compared. The critical design moment includes actions , other than the traffic loads, such as earth pressures, temperatures, and the effect of combination factors. The comparison is shown in Figure 63.

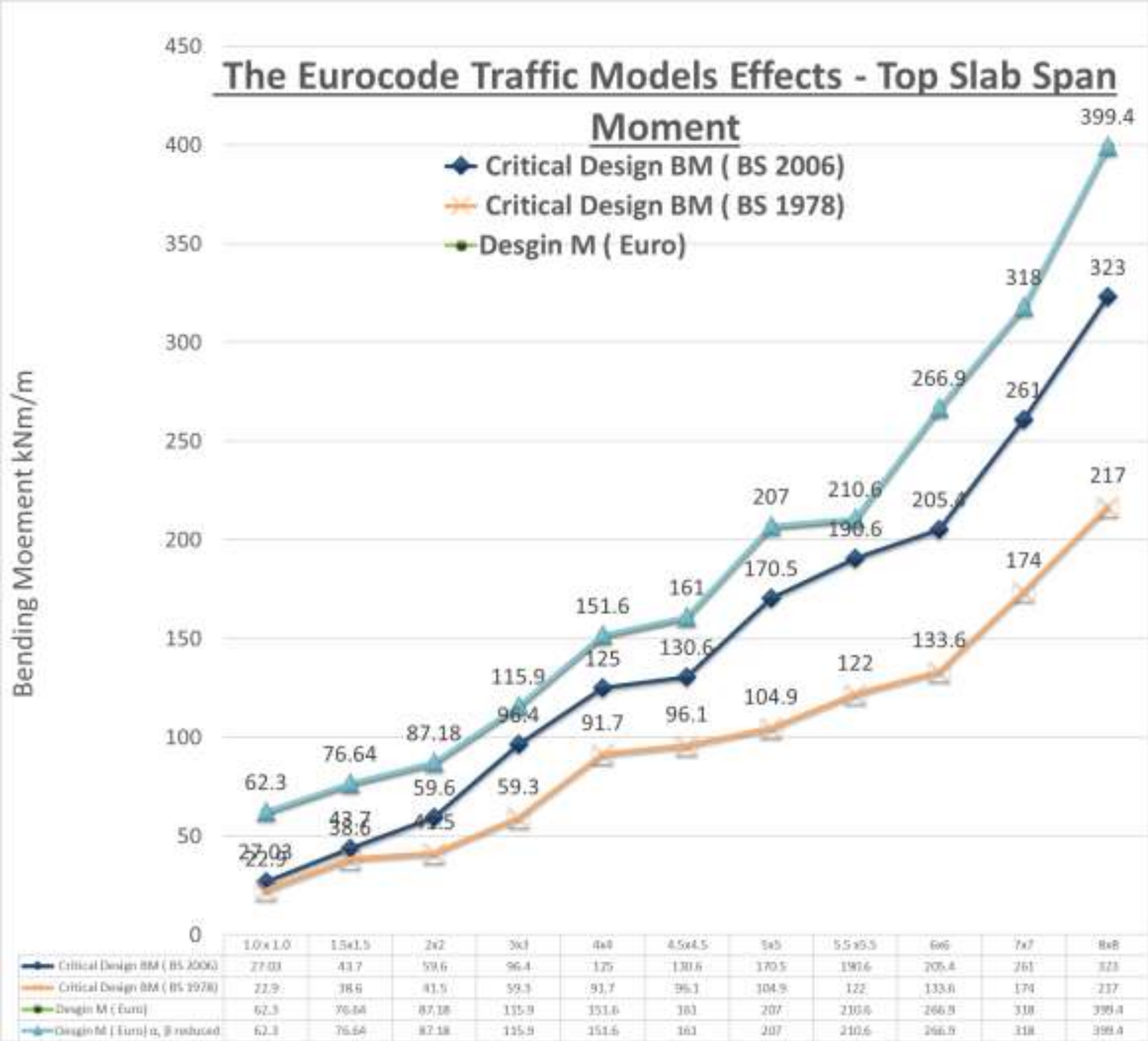


Figure 62 :Comparison of BS & Eurocode Critical Load Combinations from the Bending Moment Envelop

Considering the critical ULS top span moments for Eurocode and BS loads taken from relevant bending moment envelops, it is clear that BS 2006 loads are less than the Eurocode loads for each configuration of box culverts. The difference of the bending moment induced owing to Eurocode & BS 2006 loading amounts to 9% to 57% with a mean of 25% and a standard deviation of 14, as shown in Table 11.

Amongst the box configuration considered, from 1x1 to 3x3, the shortest span boxes of all, the critical BM of Eurocode is owing to load combination originated from characteristic values of Load Model 2. Explicitly, the combination action, 1.35 $G_{kj, sup}$ + 1.0 $G_{kj,inf}$ + 1.35 gr1b (Characteristic of LM2), provides the critical effect as shown in Figure 64.

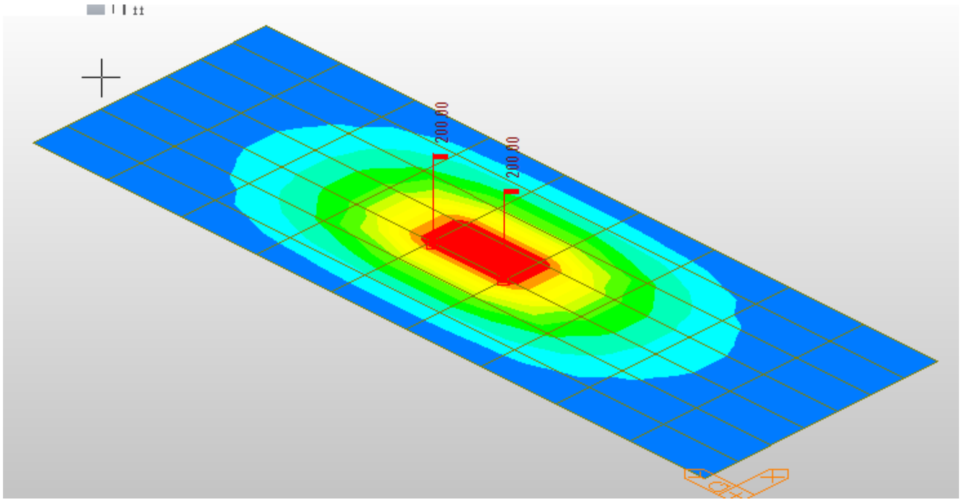


Figure 63 : Critical Load Application for Load Model 2

The greater span Box Culverts, i.e. 4x4 to 8x8, the LM1 is critical and combination of action $1.35\ G_{kj,\ sup} + 1.0\ G_{kj,inf} + 1.35\ \ (TS+UDL+q_{fk}) + 1.5x\ 0.6T_k$ is the critical combinations of actions, explicitly as shown in Figure 65.

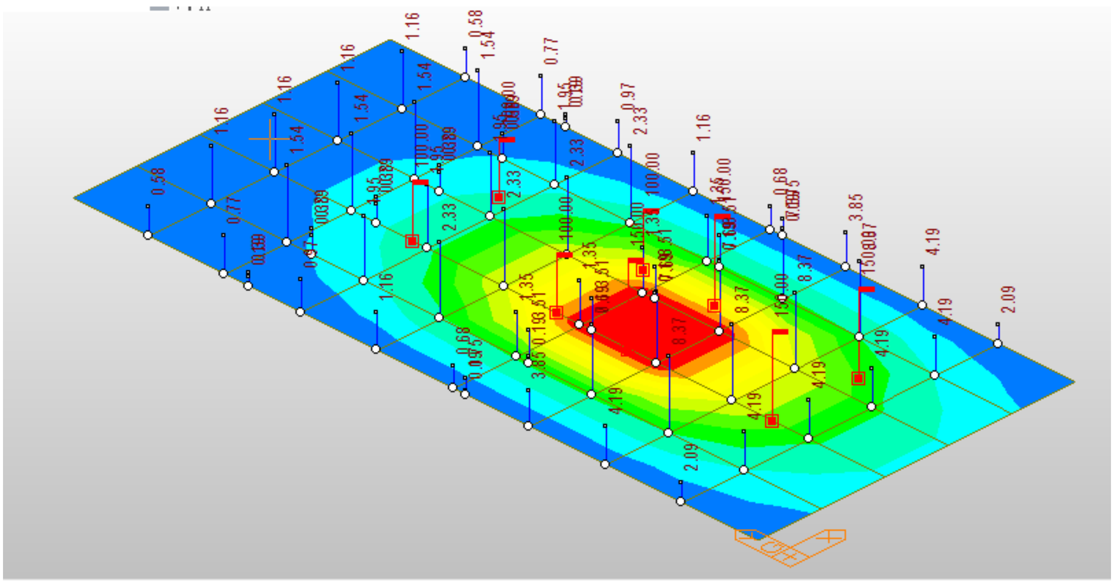


Figure 64 : Critical Load application for Load Model 1

When considering the sample population of box culverts between 1x1 to 3x3, where LM-2 is critical in Eurocode traffic loads, the BS 2006 load effects are 63% of Eurocode load effects in average. . However, where LM-1 is critical, which included the larger spans of 4x4 to 8x8, the BS 2006 loads are 82% of Eurocode loads in average . In some explicit cases, i.e. 5.5 x 5.5 box, the BS 2006 loads are 91% of EC.

Table 11 : Difference of BM owing to Eurocode and BS 5400: 2006

	Difference (EC-BS-2006)	% (EC-BS-2006)	% BS/EC
1.0 x 1.0	35.27	57%	43%
1.5 x 1.5	32.94	43%	57%
2 x 2	27.58	32%	68%
3 x 3	19.5	17%	83%
4 x 4	26.6	18%	82%
4.5 x 4.5	30.4	19%	81%
5 x 5	36.5	18%	82%
5.5 x 5.5	20	9%	91%
6 x 6	61.5	23%	77%
7 x 7	57	18%	82%
8 x 8	76.4	19%	81%
Mean	**38.52**	**25%**	**75%**
S.D	**18.39**	**14%**	**14%**

However, for complete set of box culverts, there is no significant difference between the effects of two load cases between BS 2006 and Eurocode as shown in table 11. Despite that the Eurocode load effects are higher than the BS 2006 load effects in each configuration of box culverts, it is difficult to establish an appropriate reduction factor for Eurocode loads to match BS 2006, with a significant level of confidence.

When considering the load effects of BS 1978 and Eurocode , it is clear that Eurocode loads are significantly higher than of the BS 1978 load effects. The difference of the bending moment induced owing to Eurocode & BS 2006 loading amounts to a minimum of 37% to a maximum of 60% with a mean of 48% and a standard deviation of 7, as shown in Table 12.

When considering all box culverts, the BS 1978 loads effects are 52% of Eurocode , averagely, with a standard deviation of 7. Therefore, it can be established that BS 1978 loads are 66% (mean – 3x Standard deviation) of the Eurocode loads with a 95% level of confidence. In view of generalising the case, we can further smoothen the statement that the BS 1978 loads are 70%

of the Eurocode loads, and accordingly, same reduction factors can be recommended for Eurocode load models to match BS 1978 loads.

Table 12 : Difference of Bending Moments between Eurocode and BS (5400) :1978

	Difference (EC-BS-1978)	% (EC-BS-1978)	% BS/EC
1.0 x 1.0	39.4	63%	37%
1.5 x 1.5	38.04	50%	50%
2 x 2	45.68	52%	48%
3 x 3	56.6	49%	51%
4 x 4	59.9	40%	60%
4.5 x 4.5	64.9	40%	60%
5 x 5	102.1	49%	51%
5.5 x 5.5	88.6	42%	58%
6 x 6	133.3	50%	50%
7 x 7	144	45%	55%
8 x 8	182.4	46%	54%
Mean	**86.81**	**48%**	**52%**
S.D	**48.21**	**7%**	**7%**

This reduction amount is in line with the previous study of similar comparison between the load effects of Eurocode and BS 1978, by Seyanathan and Jayasinghe, 2013, conducted for a larger span between 10m to 31m. That study recommends, a 70% reduction of the Eurocode loads for design of B, C, D & E class roads.

4.4 Comparison of the Reduced Eurocode traffic Loads against BS Traffic Loads

Based on the outcome of section 4.3, the reduced EC load is applied to the finite models. The EC loads are reduced as per the guidelines provided in the Eurocode , where minimum reduction adheres as allowed.

Accordingly, the following reduction for parameter α is derived for LM 1 load model and given in Table 13.

Table 13 : Proposed parameters LM1 for Sri Lankan roads excluding expressways, A & B class roads

Lane	EN 1991-2		Minimum Recommended by EN 1991-2		Proposed values for SL National Annex	
	TS (kN)	UDL (kN/m^2)	TS (kN)	UDL (kN/m^2)	TS (kN)	UDL (kN/m^2)
Lane 1	1.0	1.0	0.8	0.8	0.8	0.8
Lane 2	1.0	1.0	No restriction & as per NA	1.0	0.8	1.0
Lane 3	1.0	1.0	No restriction & as per NA	1.0	0.8	1.0
Other	N/A	1.0	N/A	1.0	N/A	1.0
Remaining Area	N/A	1.0	N/A	No restriction & as per NA	N/A	1.0

The reduction factors of β, the LM 2, is as below in Table 14. Like LM 1, the minimum reduction is carried out as allowed in the Eurocode .

Table 14 : Proposed parameters LM2 for Sri Lankan roads excluding expressways, A & B class roads

Location	EN 1991-2	Recommended by EN 1991-2	Proposed values for SL National Annex
	TS (kN)	TS (kN)	TS (kN)
Carriageway	1.0	same as α_{Q1} which is minimum of 0.8	0.8

Once finite models have been revised in conjunction with the reduced Eurocode loads, the resulting critical structural effects are compared. The results are shown in Figure 66.

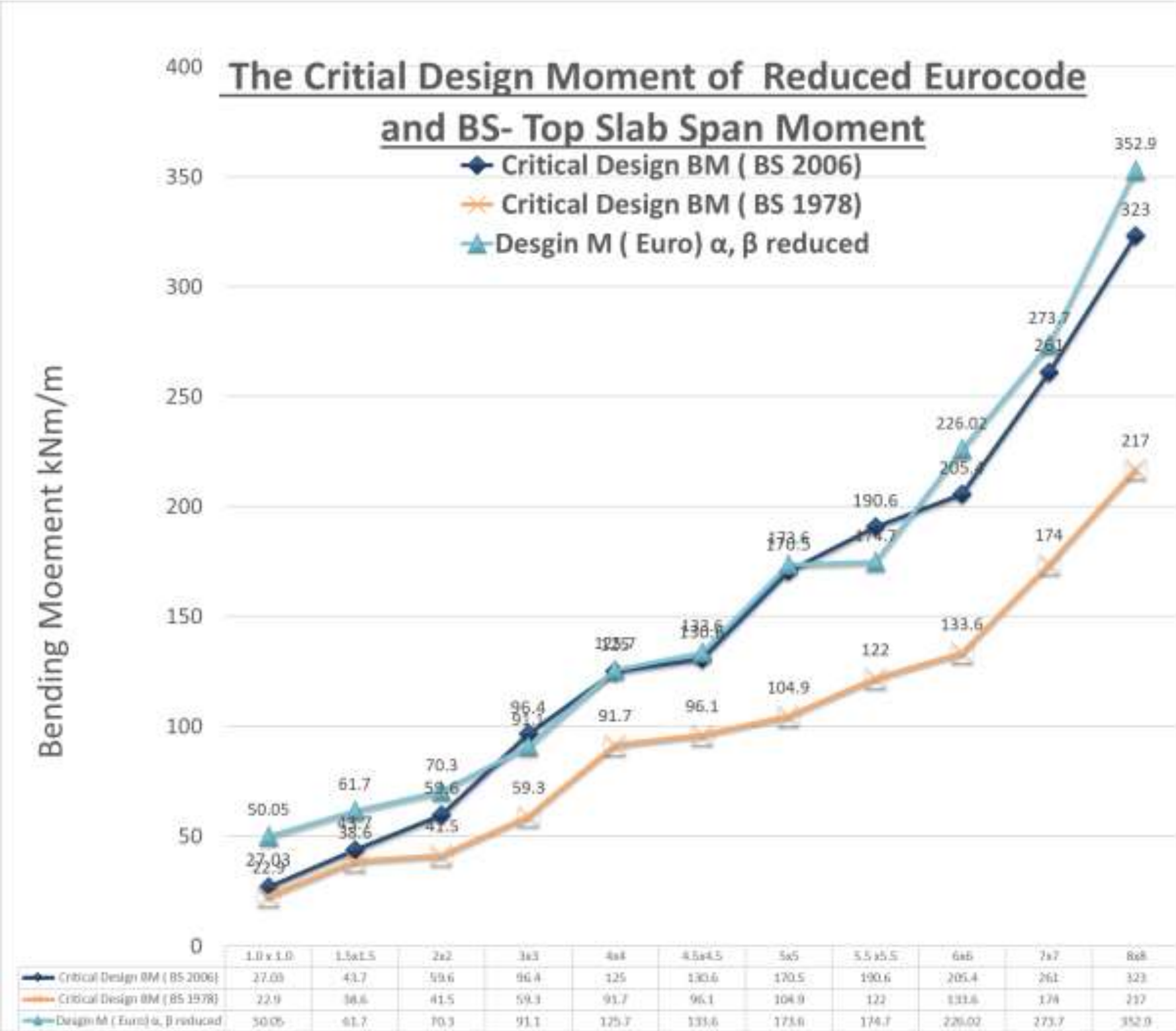


Figure 65 : Comparison of BM with Reduced Parameters for LM1 and LM2 of EC along with BS

The difference of the bending moment induced owing to reduced Eurocode & BS 2006 loading amounts to -9% to 46% with a mean of 9% and a standard deviation of 16%, as shown in Table 15.

Table 15 : Comparison of BM of Reduced EC Loads and BS 5400;2006

Box Configuration	Difference (Reduced EC-BS 2006)	% (Reduced EC-BS 2006)	% BS 2006/Reduced EC
1x1	23.02	46%	54%
1.5x1.5	18	29%	71%
2x2	10.7	15%	85%
3x3	-5.3	-6%	106%
4x4	0.7	1%	99%
4.5x4.5	3	2%	98%
5x5	3.1	2%	98%
5.5x5.5	-15.9	-9%	109%
6x6	20.62	9%	91%
7x7	12.7	5%	95%
8x8	29.9	8%	92%
Mean	**9.14**	**9%**	**91%**
S.D	**13.52**	**16%**	**16%**

However, when compared with the load effects of BS 5400 : 1978 along with reduced loads effects of Eurocode in conjunction with Table 16, it is observed that structural effects of the reduced Eurocode are higher than the effects of BS 5400: 1978 , for each and every case considered. The difference of the bending moments, induced owing to reduced Eurocode & BS 5400 : 1978 , loading amounts to 27% to 54% with a mean of 37% and a standard deviation of 8%, as shown in Table 16.

Table 16 : Comparison of reduced EC loads with BS 5400 :1978 loads

Box Configuration	Difference (Reduced EC-BS 1978)	% (Reduced EC-BS 1978)	% BS 1978/Reduced EC
1x1	27.15	54%	46%
1.5x1.5	23.1	37%	63%
2x2	28.8	41%	59%
3x3	31.8	35%	65%
4x4	34	27%	73%
4.5x4.5	37.5	28%	72%
5x5	68.7	40%	60%
5.5x5.5	52.7	30%	70%
6x6	92.4	41%	59%
7x7	99.7	36%	65%
8x8	135.9	39%	61%
Mean	**57.4**	**37%**	**63%**
S.D	**37.2**	**8%**	**8%**

Therefore, the reduced Eurocode loads closely complement with BS 1978 loads, and we can predict that difference between loads of the two codes of practice would be 21% (Mean = 3x standard deviation) with a 95% level of confidence. Emphasis is made that reduced Eurocode loads are always higher than BS 5400 :1978 values.

5.0 The Design for Eurocode & BS

Unlike in the previous BS design practice, where guidelines were provided based on structural element-wise, the Eurocode provides design guidelines based on the structural phenomena.

5.1 Steel Reinforcement

Characteristic yield strength of the steel, f_{yk}, in Eurocode is 500MPa while same is defined as 460 MPa in Table 5 of the BS 5400-4:1990. The same is shown in Figure 67 and Figure 68 below.

Designation	Nominal sizes	Characteristic strength, f_y
	mm	N/mm^2
Grade 250 (BS 4449)	8, 10, 12, and 16	250
Grade 460 (BS 4449)	All sizes	460
Cold reduced steel wire (BS 4482)	Up to and including 12	485

Figure 66 : Table 6 of the BS5400(4) : Strength of Reinforcement (BSI, 2006)

Property	Class		
	A	B	C
Characteristic yield strength f_{yk} or $f_{0.2k}$ (MPa)	500	500	500
Minimum value of $k = (f_t/f_y)_k$	≥ 1.05	≥ 1.08	≥ 1.15 < 1.35
Characteristic strain at maximum force ε_{uk} (%)	≥ 2.5	≥ 5.0	≥ 7.5

Notes
Table derived from BS EN 1992-1-1 Annex C, BS 4449: 2005 and BS EN 10080. The nomenclature used in BS 4449: 2005 differs from that used in Annex C and used here.

Figure 67 : Characteristic Steel Yield Strength as per Eurocode (Narayanan & Goodchild, 2006)

Though characteristic yield strength of the steel is defined as 500 MPa, the fundamental theories and detailing recommendations provided by the Eurocode are valid for reinforcement with characteristic yield strength of 400 MPa to 600 MPa (clause 3.2.2 (3) : EN1992-1-1)

5.2 Concrete Grade

In Eurocode class of the concrete is defined by the characteristic compressive cylinder strength (f_{ck}) and the characteristic cube strength ($f_{ck,cube}$) which is in conjunction with code EN 206-1. The Figure 69 provide the properties of various strength class of Concrete in conjunction with Eurocode.

In BS, characteristic strength of the concrete (f_{cu}) is referred to as cube strength in accordance with BS 5.1.4.2 of BS 5400.

C25/30 is selected where characteristic cylinder strength is 25 MPa, and characteristic cube strength is 30 MPa.

Property	Strength class (MPa)										
	C12/15	C16/20	C20/25	C25/30	C30/37	C35/45	C40/50	C45/55	C50/60	C28/35 a	C32/40 a
f_{ck}	12.0	16.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0	28.0	32.0
$f_{ck,cube}$	15.0	20.0	25.0	30.0	37.0	45.0	50.0	55.0	60.0	35.0	40.0
f_{cm}	20.0	24.0	28.0	33.0	38.0	43.0	48.0	53.0	58.0	36.0	40.0
f_{ctm}	1.6	1.9	2.2	2.6	2.9	3.2	3.5	3.8	4.1	2.8	3.0
$f_{ctk,0.05}$	1.1	1.3	1.5	1.8	2.0	2.2	2.5	2.7	2.9	1.9	2.1
$f_{ctk,0.95}$	2.0	2.5	2.9	3.3	3.8	4.2	4.6	4.9	5.3	3.6	3.9
E_{cm} (GPa)	27.0	29.0	30.0	31.0	32.0	34.0	35.0	36.0	37.0	32.0	33.0

Note
a Derived data

Figure 68 : Properties of Concrete (Narayanan & Goodchild, 2006)

5.3 Cover to Reinforcement

The nominal cover is defined in Eurocode as below.

$C_{nom} = C_{min} + \Delta C_{dev}$

Here C_{min} is derived based on the various factors such as 1. Safe transmission of bond forces 2. Protection against corrosion 3. Fire resistance.

ΔCdev is an allowance made for deviation, and generally recommended value is 10mm. However, in the presence of a quality assurance system to assure the concrete cover, this could be 10mm> ΔCdev >5mm

Conjunction to clause 4.4.1.2, EN 1992-1-1, Cmin

Exposure Class – XC4

Structural Classification is to be derived for the Eurocode based on the various factors ans these are give by Figure 70. The calculated structure classification is 4 +2-1-1-1=3

Structural Class							
Criterion	Exposure Class according to Table 4.1						
	X0	XC1	XC2 / XC3	XC4	XD1	XD2 / XS1	XD3 / XS2 / XS3
Design Working Life of 100 years	increase class by 2	increase class by 2	increase class by 2	increase class by 2	increase class by 2	increase class by 2	increase class by 2
Strength Class [1) 2)]	≥ C30/37 reduce class by 1	≥ C30/37 reduce class by 1	≥ C35/45 reduce class by 1	≥ C40/50 reduce class by 1	≥ C40/50 reduce class by 1	≥ C40/50 reduce class by 1	≥ C45/55 reduce class by 1
Member with slab geometry (position of reinforcement not affected by construction process)	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1
Special Quality Control of the concrete production ensured	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1	reduce class by 1

Figure 69 : The Structural Class defined by Eurocode

Accordingly following valued were derived, shown in Table 17, for Cmin and Nominal cover is taken as 35mm

Table 17 : Calculation of Cover to Reinforcement based on EN 1992-1-1

Cover (mm)	C min,b	C min,dur	c_{min} Max($c$min,b & $c$min,dur , 10mm)	ΔC_{dev}	$\mathbf{C_{nom}}$ = c_{min+} ΔC_{dev}
Bottom face of the Slab	25	20	25	10	35

However, the selection of cover to reinforcement in BS is very straightforward where nominal cover is decided as per Table 13 of BS 5400 as depicted in Figure 71.

Environment	Examples	Nominal cover[a] (mm) Concrete grade 25	30	40	50 and over
Extreme Concrete surfaces exposed to: abrasive action by sea water or water with a pH ⩽ 4.5	Marine structures Parts of structure in contact with moorland water	[b]	[b]	65[c]	55
Very severe Concrete surfaces directly affected by: de-icing salts or sea water spray	Walls and structure supports adjacent to the carriageway Parapet edge beams Concrete adjacent to the sea	[b]	[d]	50[c]	40
Severe Concrete surfaces exposed to: driving rain or alternate wetting and drying	Wall and structure supports remote from the carriageway Bridge deck soffits Buried parts of structures	[b]	45[c]	35	30
Moderate Concrete surfaces above ground level and fully sheltered against all of the following: rain, de-icing salts, sea water spray Concrete surfaces permanently saturated by water with a pH > 4.5	Surface protected by bridge deck water-proofing or by permanent formwork Interior surface of pedestrian subways, voided superstructures or cellular abutments Concrete permanently under water	45	35	30	25

[a] Actual cover may be up to 5 mm less than nominal cover (see Part 7).
[b] Concrete grade not permitted.
[c] Air entrained concrete should be specified where the surface is liable to freezing whilst wet (see Part 7).
[d] For parapet beams only grade 30 concrete is permitted provided it is air entrained and the nominal cover is 60 mm.

Figure 70 : Cover for Reinforcement by BS 5400

Accordingly, Cover is selected as 35mm for Reinforce design conjunction to BS

5.4 Flexural Design

5.4.1 Eurocode of practice in Flexural Design

Further, Eurocode does not provide explicit flexural design formula in contrast to BS 5400 part 4 and BS 8110 part 1, which deals with the design of concrete and provide explicit flexural formula and charts. The Eurocode provides the stress block only, as shown in Figure 72, and the formula is to be generated using the first principles.

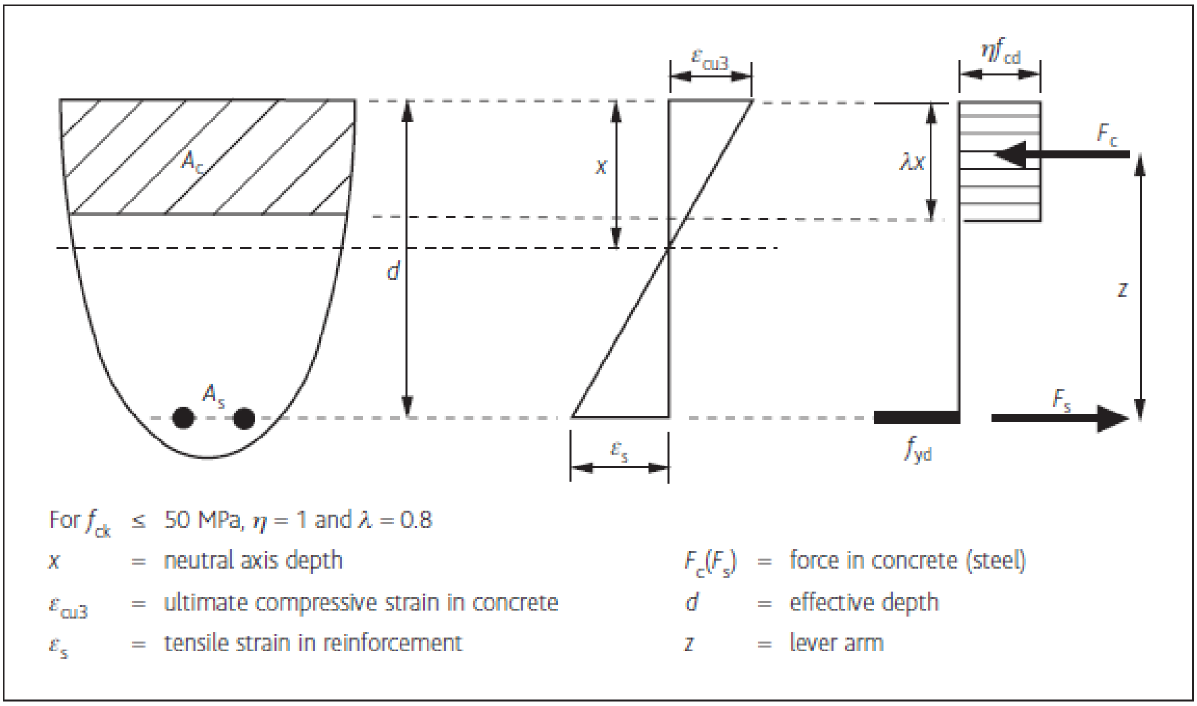


Figure 71 : ULS stress & strain (Narayanan & Goodchild, 2006)

Further, Eurocode uses the cylinder strength of the concrete in contrast to BS practice of adopting cube strength of the concrete, as given by Figure 69.

Based on the Eurocode recommended stress block, the Reinforcement for flexural have been evaluated and depicted in the Below Table 18 .

Table 18 : Evaluated Reinforcement in conjunction with Eurocode

Box Configuration	1.0 x 1.0	1.5x1.5	2x2	3x3	4x4	4.5x4.5	5x5	5.5 x5.5	6x6	7x7	8x8
Slab Thickness - mm	200	200	200	300	400	450	500	550	600	700	800
Criticla BM (EC) - kNm/m	62.3	76.64	87.18	115.9	151.6	161	207	210.6	266.9	318	399.4
RF Area - mm2	997	1283	1495	1110	1021	938	1075	980	1133	1143	1244
RF Arrangement	B12@100	B16 @150	B16@125	B16@175	B16@175	B12@100	B12@100	B12@100	B12@100	B16@175	B16@150

5.4.2 BS code of practice in flexural design

Similarly, the Reinforcement required for critical BM is evaluated in conjuction with BS and tabulated in Table 19.

Table 19 : Reinforcement evaluation report in conjunction with BS 5400

Box Configuration	1.0 x 1.0	1.5x1.5	2x2	3x3	4x4	4.5x4.5	5x5	5.5 x5.5	6x6	7x7	8x8
Slab Thickness - mm	200	200	200	300	400	450	500	550	600	700	800
Criticla BM (BS) - kNm/m	27.03	43.7	59.6	96.4	125	130.6	170.5	190.6	205.4	261	323
RF Area - mm2	444.35	732	1036	986	916	840	978	984	966	1042	1120
RF Arrangement	T10@175	T10@100	T12@100	T12@100	T12@100	T12@125	T12@100	T12@100	T12@100	T12@100	T12@100

However, BS required to check the adequacy of Reinforcement against the width of the crack, as stipulated in SLS design criteria and provided the amount of Reinforcement against the flexure may not satisfied the requirements in SLS crack width design.

5.5 Shear Design

5.5.1 BS code of practice

In conjunction with clause 5.4.4.1, part 4, BS 5400, no shear Reinforcement is required when shear stress is less than $\xi_s v_c$ where v_c is the ultimate shear strength of the concrete and ξ_s is the modification factor for depth of the slab.

The critical shear forces occur near the support of the top slab and result of the wheels of the HB type traffic loads or the KEL of HA type traffic.

Thus, provisions for enhancement of the shear, given in clause 5.3.3.3, part 4, BS 5400, are also applicable.

For moving loads, both HA and HB , the maximum shear occurs near to the support. When HB axel is placed near to the support, the maximum shar occurs at supports as shown in Figure 73 In HA , the maximum shear occurs at supports when knifed edge load (KEL) is at near the support, as shown in Figure 74.

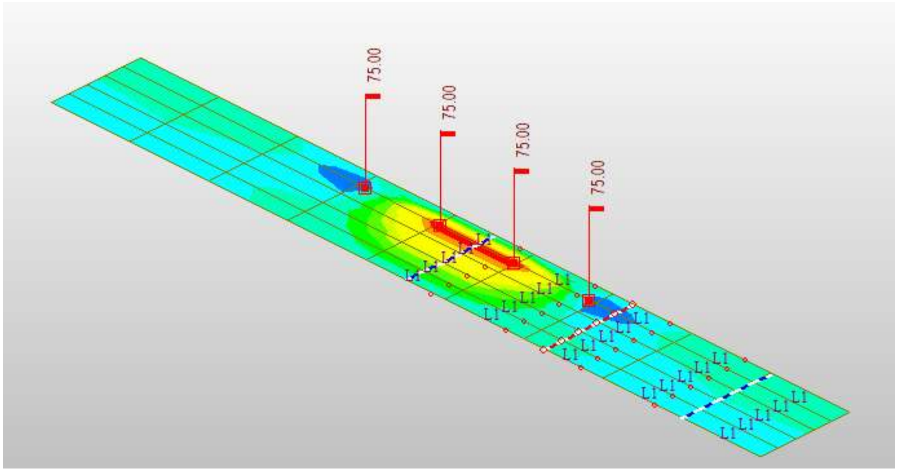


Figure 72 : Critical SF owing to HB axel in 1x1 box structure

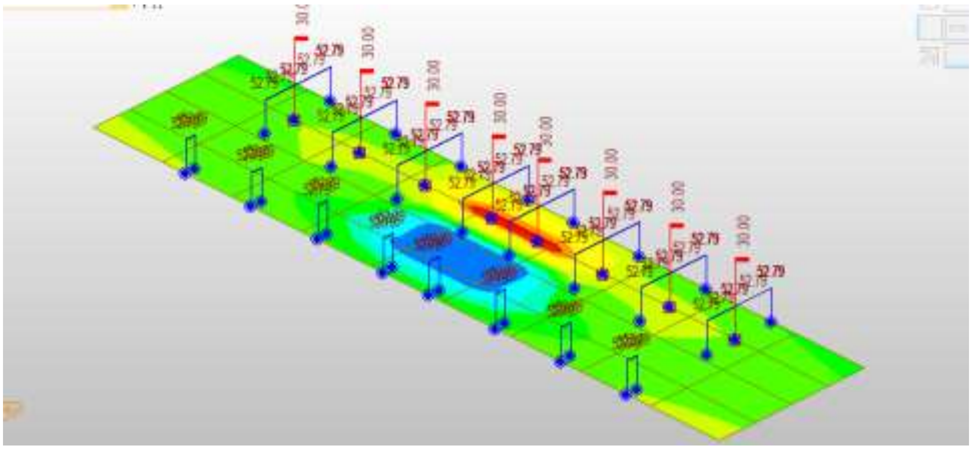


Figure 73 : Critical SF location owing to HA KEL in 2x2 box structure

Based on the shear forces obatained, the shear design has been carried out in conjuction with BS 5400 -part 4. The output of the deising is provided in Table 20. Accordingly, no shear Reinforcement is required to provide for the deck slab in configuration of box struxtures.

Table 20 . Shar Design in conjunction with BS 5400

Box Configuration	1.0 x 1.0	1.5x1.5	2x2	3x3	4x4	4.5x4.5	5x5	5.5 x5.5	6x6	7x7	8x8
Slab Thickness - mm	200	200	200	300	400	450	500	550	600	700	800
BS (ULS) shear (kN per m width)	101	126.2	130	181	153	195	191	190.8	273	449	520
Shear RF	No shear RF	No shear RF	No shear RF	No shear RF	No shear RF	No shear RF	No shear RF	No shear RF	No shear RF	No shear RF	No shear RF

5.5.2 Eurocode Practice

Similar to BS practice , no shear reinforcement is required for slabs when $V_{ED} < V_{RD,c}$ where

V_{ED} - Shear force resulting from external loads

$V_{RD,c}$ - Shear Resistance of the member without shear Reinforcement

V_{RD} - Shear Resistance of a member with shear Reinforcement including from inclined compressive and tensile chords (Brooker, et al., 2009)

In conjuction with clause 6.2.1 of Eurocode, only minimum shear to be provided when $V_{ED} < V_{RD,c}$. However, minimum shear Reinforcement can be omitted where transverse redistribution of loads is possible such as solid slab. Since top slab of the box culverts allows transverse redistribution when $V_{ED} < V_{RD,c}$ the , the shear links can be omitted.

In Eurocode , the Reinforcement design for shear is based on Strut Inclination Method where angle of strut varies with the applied forces. This is depicted in Figure 66 where Eurocode 2 limits the strut angle between minimium of 21.8 degrees and maximum of 45 degrees. (Narayanan & Goodchild, 2006).

When low intensity of shear force is met , the strut angle is less that 21.8 degress and Eurocode speacifies the minimum shear links for structral members. For higher shear forces, the strut angle will be greater than 45 degrees, thus redesign of section is required. For shear forces that created strut angle of between 21.8 degress and 45 degrees, the required shear links is caluclated based on the actual truss angle. By doing so, optimium shear likas can be found. This phenomena is explained in Figure 75.

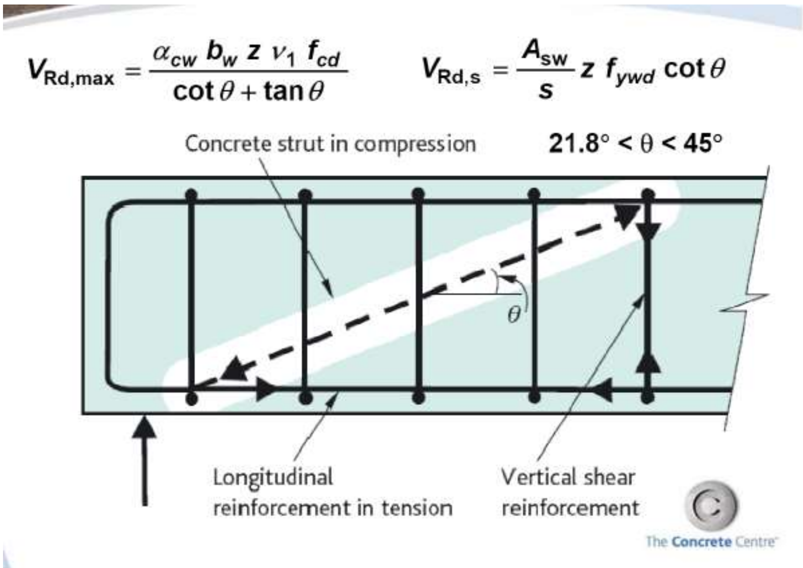


Figure 74 :Angle Struct method for Shear design in Eurocode 2 (Brooker, et al., 2009)

The studies that compared the Reinforcement design between Eurocode and BS has established a significant reduction of Reinforcement in Eurocode design against the shear resistance as shown in Figure 76 (Narayanan & Goodchild, 2006).

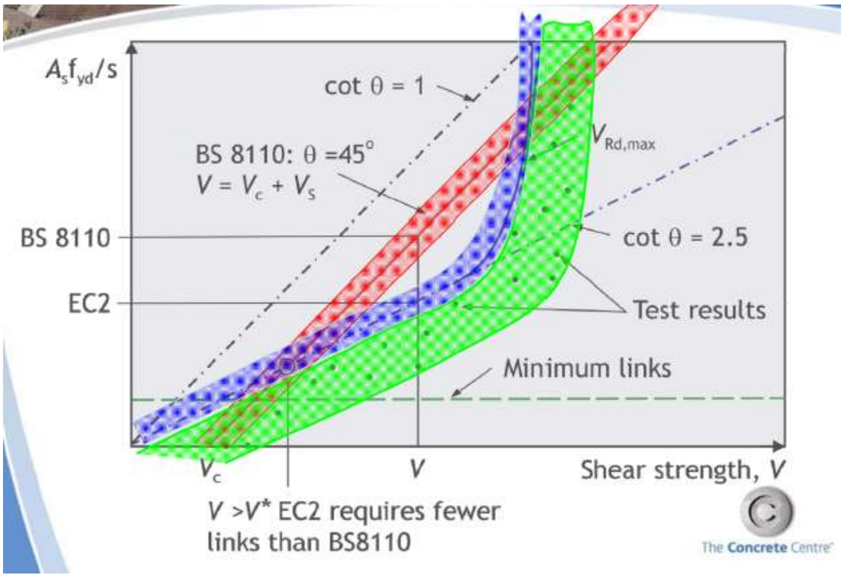


Figure 75 :Shear Reinforcement design based on the angle strut methos specified by Eurocode 2 and comparison of BS shear design (Narayanan & Goodchild, 2006).

Like BS , the ULS shear forces obatained and the shear design was conducted in accordence with Eurocode 2. Accordingly, no shear Reinforcement is required to provide for the deck slab for all configuration of box structures.

5.6 Crack Control

5.6.1 BS code of practice

The limited crack width stipulated in BS 5400(4) is much stringent than Eurocode, though, and given in Table 2 of BS 5400-4:1990. The same is depicted in Figure 77 below.

Environment	Examples	Design crack width
		mm
Extreme Concrete surfaces exposed to: abrasive action by sea water or water with a pH $\leqslant$ 4.5	 Marine structures Parts of structure in contact with moorland water	0.10
Very severe Concrete surfaces directly affected by: de-icing salts or sea water spray	 Walls and structure supports adjacent to the carriageway Parapet edge beams Concrete adjacent to the sea	0.15
Severe Concrete surfaces exposed to: driving rain or alternate wetting and drying	 Wall and structure supports remote from the carriageway Bridge deck soffits Buried parts of structures	0.25
Moderate Concrete surfaces above ground level *and* fully sheltered against all of the following: rain, de-icing salts, sea water spray Concrete surfaces permanently saturated by water with a pH > 4.5	 Surface protected by bridge deck water-proofing or by permanent formwork Interior surface of pedestrian subways, voided superstructures or cellular abutments Concrete permanently under water	0.25

Figure 77 :Table 1 of the BS 5400 -4:1990- The limiting crack width stipulate by the code of practice (BSI, 2006).

Based on the SLS design criteria stipulated in the BS 5400, the Reinforcement required to satisfying the limited crack width are being assessed and provided in Table 21 blow.

Table 21 : The summary of Reinforcement design of the SLS criteria of limiting crack width

Box Configuration	1.0 x 1.0	1.5x1.5	2x2	3x3	4x4	4.5x4.5	5x5	5.5 x5.5	6x6	7x7	8x8
Slab Thickness - mm	200	200	200	300	400	450	500	550	600	700	800
BS (SLS) critical Moment	15.4	31.1	35.7	60.8	70.8	78.4	113.7	127	136.9	174	195
Crack Width (BS)	T10@125	T12@125	T12@100	T12@100	T12@100	T12@125	T12@100	T12@100	T12@100	T12@100	T12@100
RF Area - mm2	628	905	1130	1130	1130	904	1131	1131	1131	1131	1131

It is noted that Reinforcement requirement to satisfy the SLS criteria is higher than the ULS criteria provided in section 5.4 for all the configurations of box culverts.

Thus, the serviceability limit state criteria for limiting crack width is the critical and governing case for design of flexural Reinforcement subjected to the BS code of practice and considered configuration of box structures.

5.6.2 Eurocode practice.

The limited calculated crack width W_{max} is provided under clause 7.3 in the EN1992-1-1:2004 - Design of Concrete Structures -Part 1-1: General rules and clause 7.3 rules for buildings and the EN1992-2:2005 – Design of Concrete Structures -Part 2: Concrete Bridges (Design and detailing rules). The two references have different limiting values, and the latter provide the appropriate values for the highway box structures. Figure 78 shows the applicable limitations.

Exposure Class	Reinforced members and prestressed members without bonded tendons	Prestressed members with bonded tendons
	Quasi-permanent load combination	Frequent load combination
X0, XC1	0,3[a]	0,2
XC2, XC3, XC4	0,3	0,2[b]
XD1, XD2, XD3 XS1, XS2, XS3		Decompression

[a] For X0, XC1 exposure classes, crack width has no influence on durability and this limit is set to guarantee acceptable appearance. In the absence of appearance conditions this limit may be relaxed.

[b] For these exposure classes, in addition, decompression should be checked under the quasi-permanent combination of loads.

Figure 78 : Table 7.101N of EN1992-2:2005(E) ; The recommended values of w max and relevant combination rules

The emphasis is made on the load combinations which this serviceability limit state requirement must be fulfilled. In Eurocode, the crack width is to be checked against the Quasi – Permanent Load combination while in BS, the same is carried out against the Serviceability limit state of load combinations.

Quasi Permanent Load (meaning almost permanent) combination, shown in Figure 79, is defined in EN1990:2002 under clause 6.5.3 and generally used for long term effects and the appearance of the structure.

$$\sum_{j\geq 1} G_{k,j} \text{"+"} P \text{"+"} \sum_{i\geq 1} \psi_{2,i} Q_{k,i} \qquad (6.16b)$$

-

Combination	Permanent actions G_d		Prestress	Variable actions Q_d	
	Unfavourable	Favourable		Leading	Others
Characteristic	$G_{kj,sup}$	$G_{kj,inf}$	P	$Q_{k,1}$	$\psi_{0,i}Q_{k,i}$
Frequent	$G_{kj,sup}$	$G_{kj,inf}$	P	$\psi_{1,1}Q_{k,1}$	$\psi_{2,i}Q_{k,i}$
Quasi-permanent	$G_{kj,sup}$	$G_{kj,inf}$	P	$\psi_{2,1}Q_{k,1}$	$\psi_{2,i}Q_{k,i}$

Figure 76 : Definition of Quasi Permeant combinations of actions

In conjunction with TableA2.6 of EN1990 Annex A2, the Quasi Permanent Loads are obtained for the MIDAS CIVIL Model.

The recommended ψ2 values are obtained from Table A2.1 of EN 1990 Annex A2 and reproduced as Figure 80.

Action	Symbol		ψ_0	ψ_1	ψ_2
Traffic loads (see EN 1991-2, Table 4.4)	gr1a (LM1+pedestrian or cycle-track loads) 1)	TS	0,75	0,75	0
		UDL	0,40	0,40	0
		Pedestrian+cycle-track loads 2)	0,40	0,40	0
	gr1b (Single axle)		0	0,75	0
	gr2 (Horizontal forces)		0	0	0
	gr3 (Pedestrian loads)		0	0	0
	gr4 (LM4 – Crowd loading))		0	0,75	0
	gr5 (LM3 – Special vehicles))		0	0	0
Wind forces	F_{Wk} - Persistent design situations - Execution		0,6 0,8	0,2 -	0 0
	F_W^*		1,0	-	-
Thermal actions	T_k		0,6 3)	0,6	0,5
Snow loads	$Q_{Sn,k}$ (during execution)		0,8	-	-
Construction loads	Q_c		1,0	-	1,0

1) The recommended values of ψ_0, ψ_1 and ψ_2 for gr1a and gr1b are given for road traffic corresponding to adjusting factors α_{Qi}, α_{qi}, α_{qr} and β_Q equal to 1. Those relating to UDL correspond to common traffic scenarios, in which a rare accumulation of lorries can occur. Other values may be envisaged for other classes of routes, or of expected traffic, related to the choice of the corresponding α factors. For example, a value of ψ_2 other than zero may be envisaged for the UDL system of LM1 only, for bridges supporting severe continuous traffic. See also EN 1998.

2) The combination value of the pedestrian and cycle-track load, mentioned in Table 4.4a of EN 1991-2, is a "reduced" value. ψ_0 and ψ_1 factors are applicable to this value.

3) The recommended ψ_0 value for thermal actions may in most cases be reduced to 0 for ultimate limit states EQU, STR and GEO. See also the design Eurocodes.

Figure 77 :Partial safety factors on loads (BSI, 2004)

As ψ2 values for traffic & wind forces are zero, only thermal actions are combined with the persistent loads to achieve SLS load requirements for Crack Width check.

Thus, the unique quasi permanent load combination is considered as

$G_{kj,\,sup} + 0.5T_k$

A typical bending moment diagram is shown in Figure 71 for Quasi Permeant combination for 8x 8 Box culvert.

In conjunction with Figure 81, the calculated crack width should not be greater than 0.3mm under quasi -permanent combination of actions irrespective of exposure class.

In Eurocode, the compliance to crack width is ensured vide providing the minimum amount of reinforcement as stipulated by clause 7.3.2 (102) of BS EN 1992-2

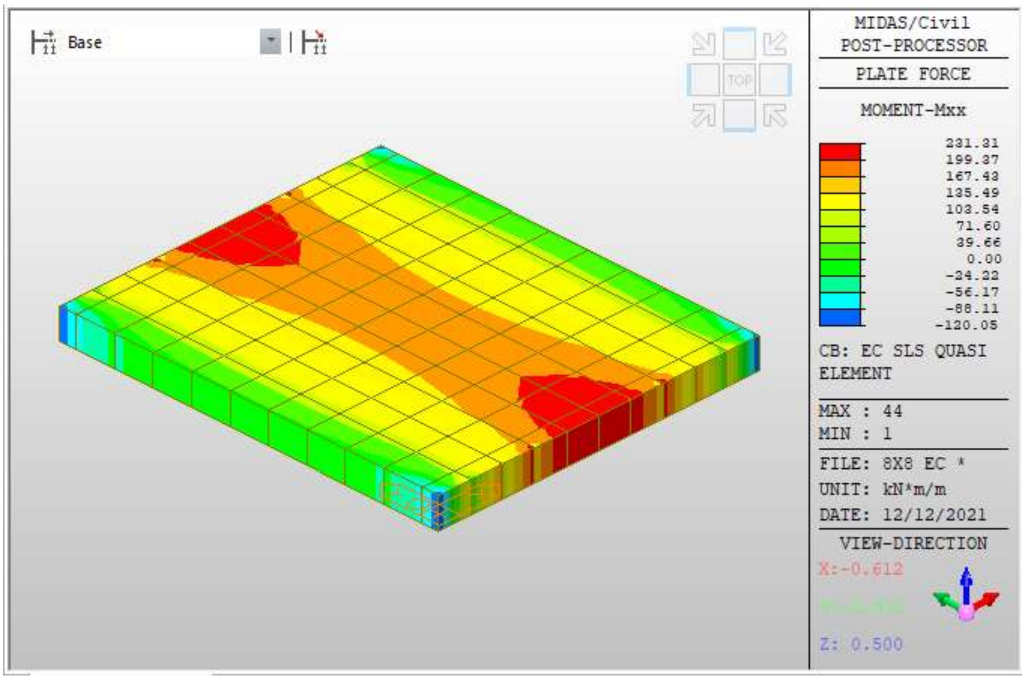


Figure 78 : SLS Bending Moment contours for Eurocode Quasi Permanent Combination in 8 x8 Box Culvert

Based on the Eurocode Quasi Permeant combination, The design of SLS crack width for 0.3 mm has been carried out and Reinforcement is provided as shown in Table 22. The calculation is carried out in conjunction with 5.4.1 , accounting the SLS requirement.

Table 22 . Summery of SLS Crack width design for Eurocode under quasi permeant combinations

Box Configuration	1.0 x 1.0	1.5x1.5	2x2	3x3	4x4	4.5x4.5	5x5	5.5 x5.5	6x6	7x7	8x8
Slab Thickness - mm	200	200	200	300	400	450	500	550	600	700	800
EC (SLS) Quasi Permenant BM	7.48	10.9	12.5	30.4	45.3	50.5	71.6	94.2	110.8	160.3	231.8
Crack Width (BS)	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok	ok

5.7 Comparison of Reinforcement Between Eurocode and BS

Having designed for all the requirement stipulated by Eurocode and BS , i.e flexural, shear and cracking , the final outcome for Reinforcement amounts are tabulated below for all the configuration of box culvert in Table 23..

Table 23 ; Comparison of Reinforcement requirement between Eurocode and BS

Box Configuration	1.0 x 1.0	1.5x1.5	2x2	3x3	4x4	4.5x4.5	5x5	5.5 x5.5	6x6	7x7	8x8
Slab Thickness - mm	200	200	200	300	400	450	500	550	600	700	800
Critical RF Area for BS	628	905	1130	1130	1130	904	1131	1131	1131	1131	1131
Critical RF Area for EC	997	1283	1495	1110	1021	938	1075	980	1133	1143	1244
Difference	369	378	365	-20	-109	34	-56	-151	2	12	113
% Difference/EC	37%	29%	24%	-2%	-11%	4%	-5%	-15%	0%	1%	9%
%BS/EC	63%	71%	76%	102%	111%	96%	105%	115%	100%	99%	91%

It is noted that for some cases the BS providing greater amount of Reinforcement as shown in Table 23. This is different from the outcome of results for bending moments, discussed in section 4.3 where , for all the cases, the bending moment induced from Eurocode were high with greater margin.

When finding the reasons for above phenomena, the BS has much stringent criteria for design for SLS crack width. In BS, the crack width limitation is set for 0.25mm , as shown in Figure 68, and described in section 5.6.1. The requirement stipulated by the Eurocode is 0.3 mm for all the exposure class as described section 5.6.2 and shown in Figure 69.

Further BS crack width is checked for SLS load combinations including the traffic loads. However, as described in 5.6.2 , the Eurocode requirement for crack width is only for Quasi permeant loads which excluding of the traffic loads.

Therefore, as resultant of stringent crack width limitation and the incorporation of traffic loads, the final Reinforcement amount for BS is much higher than Eurocode, for some cases.

6.0 Conclusion

In the context of obsolete BS codes in the design of highway structures, the adoption of Eurocode is inevitable for Sri Lanka in the near future. In this regard, the preparation of National Annexures to the Eurocode is essential, and it should be harmonised with the present highway structure design practice to avoid significant cost escalation while maintaining structural safety and durability having a provision for increasing highway loading.

This study addresses the above issue in the context of box culverts and underpasses where the emphasis is made on the highway traffic and other associate loads such as soil-structure interaction of the box culvert and temperature effects.

It is found that for small spans, the LM1 and LM2 load cases provide the critical traffic load effects for the box culvert. The LM3 is not critical in any of the cases considered. The SV 80 has been considered for LM 3, and it is equivalent to 30 HB units defined in the present RDA bridge design practice for Sri Lanka..

When considering the load actions of BS 2006 along with Eurocode, there is no significant difference, although that BS 5400 (2006) loads are 25% lesser in average of Eurocode loads with standard deviation of 14. This difference is further diminishing with the outcome of reinforcement design.

However, there is a significant difference between Eurocode loads & BS 1978, and this study has established that 70% of the Eurocode loads can be considered to harmonise with the BS 1978 loads.

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7.0 Recommendations

In Eurocode, abnormal vehicle traffic is represented by Load Model 3. However, vehicles with severe load effects, other than SV 80, can be introduced as required via national annexes. In that regard, to be realistic, more research is required to establish the appropriate vehicle to represent the abnormal vehicle load conditions in the context of present and future highway vehicle usage in Sri Lanka

Since present expressway & highway designs are conducted in conjunction with the latest version of the BS, i.e. BS 2006 loads, it is recommended to adopt the Eurocode loads as it is, without changing the default values of α and β in future preparation of National Annexes.

However, the rural roads which include class C, D & E, where most of the structures are functioning well without any structural defects owing to highway loads, and which have been already designed according to BS 1978 version, a reduction of α and β is recommended.

In this regard, it is recommended to adopt different loads specification for Expressways, National Highways and Rural Roads separately, in view of optimising the safety, cost and durability of the structures. This concept is in line with the UK strategy in preparation of National Annexures as well.

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