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Ultimate Limit State (ULS) to Serviceability Limit State (SLS) Load Conversion Factors for Building Foundation Design

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ABSTRACT

The need to evolve new concepts for converting aggregated ultimate loads back to service loads has become pertinent. This is due to the existence of shortcomings inherent in existing load conversion factors, the need to ensure speedy and less cumbersome service load computation process and the need for cost effective foundation design. This study thus aims at addressing these shortcomings and evolving suitable and practicable options of computing service loads. Research design adopted for this study was observational studies (particularly modelling and simulation).Reinforced concrete structural models were developed and simulated for differing live load values using Orion 18 software to obtain foundation loads(ultimate (factored) loads and service (unfactored) loads) from which the load conversion factors were computed. New values of load conversion factors were evolved and a relationship between the live load and load conversion factor was also established and detailed. The study concluded that the load conversion factors obtained and the relationship established are suitable and applicable. The application of these new load conversion factors in building foundation design and its inclusion in design codes and standards is recommended. The implication of this is timely delivery of design jobs and a cost effective foundation design.

Keywords: Load conversion factor, ultimate load, service load

INTRODUCTION

Conversion of ultimate (factored) loads back to service (unfactored) loads is an alternative concept employed in obtaining service loads for foundation design purposes. According to Oyenuga (2001), loads from the superstructure are more often than not aggregated at the ultimate limit state. Most codes such as BS 8004(1986), ACI 318-11(2011), Euro code 1997 Part 1(2004) among others require that the base area of footings or the number and arrangement of piles be determined from unfactored forces and moments transmitted by footing to soil. Since re-computation of loads to obtain service loads are relatively cumbersome and time consuming, a load conversion factor is employed to convert these aggregated column ultimate loads back to service loads before being used for serviceability limit state foundation design purposes. Values of conversion factors are a function of the magnitude of different types of loads and as such, a singular value may not be relied upon. It is thus important that appropriate conversion factor values be sought for or evolved where possible so as to provide the much needed data for load conversion purposes.

LITERATURE REVIEW

Oyenuga(2001) discovered through experience that the ultimate load could be divided by a factor of 1.46 to convert to service load, finding this to be within reasonable practical limits and further adding that this value may increase to 1.49 as the structure's live load increases to 5.0kN/m^2.

Also, BS 5950 Part 1(2000) detailed in Clause A6 a ratio ((factored load)/(service Load)), stating that the factor is generally about 1.50 with a minimum of 1.40. The ratio specified here is similar to that of Quimby (2008) who referred to the factor as composite load factor i.e. the ratio of load combination result to the algebraic sum of individual load components.

In the revised Acceptance Criteria for Anchor Bolts i.e. AC 193, the International Code Council-Evaluation Service(ICC – ES)(2012) detailed a conversion factor, viewing it as a weighted average of load factors for any given controlling load combination. It is computed only when individual load components are known and a load combination equation is defined. This concept seems more cumbersome as service loads will have to be known first before the conversion factor can be obtained. This concept is ideal for data generation purposes, but not for immediate application during design.

So far, Values of load conversion factors were only specified by Oyenuga (2001) and BS 5950 Part 1(2000) and the values of load conversion factor specified by Oyenuga (2001) falls within the limit(i.e. $1.40 \leq$ ratio ≤ 1.5) contained in BS 5950 Part 1(2000). Quimby (2008) and AC 193 (2012) only specified methods of computing the factor.

Most reinforced concrete design codes were mute on load conversion factors. A thorough and critical view into the British Standards (BS 8110 part 1(1997), BS 6399 part 1(1984) and BS 8004 (1986)), the Eurocodes (EN 1990(2002), EN 1991-1-1(2002), EN 1992-1-1(2004), EN 1993-1-1(2005) and EN 1997-1(2004)), Canadian Standards Association's A23-3-04(2004), Bureau of Indian Standards' IS 456:2000, Joint Australia/New Zealand's AS-NZS 1170-2(2000), New Zealand Standard NZS 3101-1(2006), ACI 318-11(2011) and ANSI/AISC 303-16(2016) will reveal the absence of load conversion factors. Also, Hong Kong's Building Department Codes of Practice for Structural use of steel (2011), Structural Use of Concrete(2013) and Foundations(2004) as well as the Japanese Society of Civil Engineers' 'JSCE (2010) Standard Specification for concrete Structures – 2007' contained no details on load conversion factors. This development suggests that load conversion factors have not been considered relevant design parameters.

The call for caution in the application of the conversion factor of 1.46 alongside the recommendation for generation of load conversion factors for various values of live loads by Oyenuga (2001) suggests the existence of unknown issues which might hamper outcomes of its application if not known and controlled. Also, the existing values of load conversion factors are inconclusive and also not specific as they were either discovered through experience or not definite. It is thus pertinent to seek for appropriate, reliable and suitable Load conversion factors that will be globally acceptable and applicable to help address the short comings of the existing ones.

METHODOLOGY

Observational studies, modelling and simulation in particular, was adopted as the primary method of data collection. Modelling and simulation scheme proposed by Velten (2009) was adopted for this work and it involves problem definition, system analysis, modelling, simulation and validation.

Problem Definition

Two sets of aggregated loads which are the major data for this purpose were required. The first set of aggregated loads are the factored loads or ultimate loads i.e. loads at the ultimate limit state while the second set of aggregated loads are the unfactored loads or working loads i.e. loads at the serviceability limit state. Theseiv. loads were obtained at the foundation level i.e. foundation loads (ground column loads) computed and collated at both the ultimate limit state and serviceability limit state.

System Analysis

The system is a network of reinforced concrete structural members comprising of beams, slabs columns and walls. Dimensions of structural members adopted are

i. Slab – 150mm thick.
ii. Beams – 230mm x 450mm.
iii. Walls (sandcrete block) – 230mm thick.

Columns – 230mm x 230mm.

The loads on the system consist of dead loads (from slabs, beams, walls, columns, roof and finishes) and live loads. These loads were factored by their appropriate factors of safety to obtain values at the ultimate limit state. A value of 1.4 and 1.6 was adopted for dead loads and live loads respectively. The unfactored loads were taken as values for the serviceability limit state.

Basic weights of various materials adopted are as detailed by Oyenuga(2001) and are as follows:

i. Concrete……………………………….…24.00 KN/m³
ii. Screed (floor)………………………………0.225KN/m²
iii. 225mm partition block wall …………….... 2.87KN/m²
iv. 150mm partition block wall……………….. 2.27KN/m²
v. Roof live load……………………………1.50KN/m²
vi. Wall finishes (both sides)…………………….…….. 0.60KN/m²
vii. 13mm rendering ……………………………..…. 0.30KN/m²
viii. 37mm screeding……………………….......….. 0.80KN/m²
ix. Roofing felt and screed…………………………. 2.00 KN/m²
x. Roof live loads –with access………………...….. 0.25 KN/m²
xi. Wood (average)……………………………..... 8.00 KN/m²
xii. Asbestos roofing sheet, sheeting rails and nails…. 0.40 KN/m²
xiii. Amiatus and nails………………...………………0.30 KN/m²

Live loads values considered were obtained from BS 6399 Part1:1984 and are 1.5 KN/m², 2.0 KN/m², 2.5 KN/m², 3.0 KN/m², 4.0 KN/m², 5.0 KN/m², 7.5 KN/m², 9.0 KN/m², 10.0 KN/m², 12.0 KN/m² and 20.0 KN/m². (BS 6399 Part 1. 1984)

The self weight and dimensions of the foundations elements were ignored at this stage because it was assumed they are not known and are functions of the aggregated loads from the beams, slabs walls and columns.

The data enumerated in the system analysis were used in generating the model. The model which incorporated the details above is presented in 2D and 3D as show in the figures 1, 2 and 3 below.

Modelling

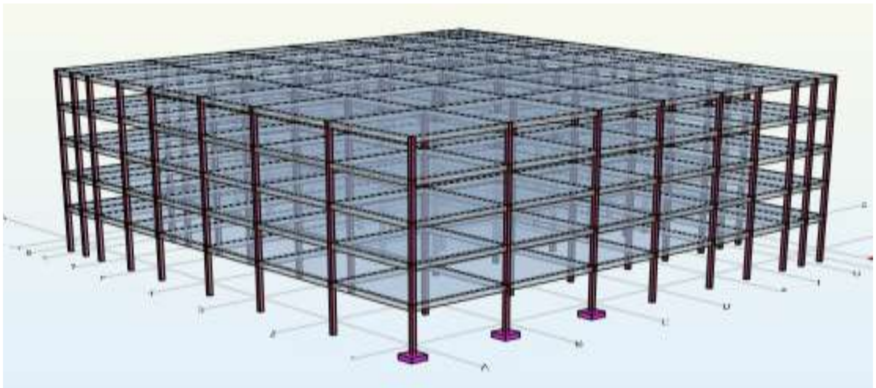

Figure 1: Typical Three Dimensional View of Reinforced Concrete Structural Model

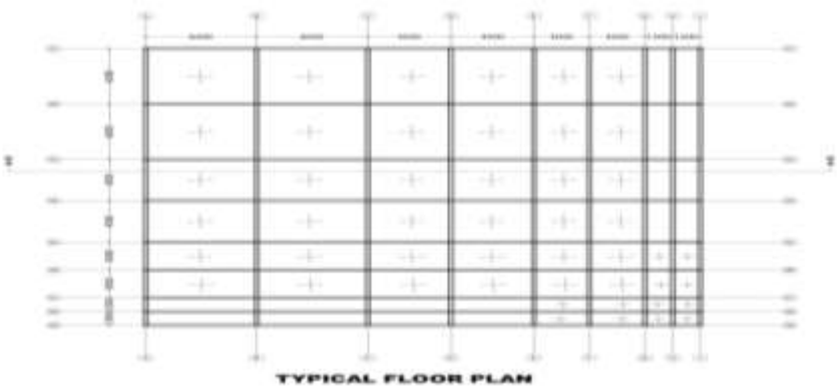

Figure 2: Typical Floor Plan of Reinforced Concrete Structural Mode

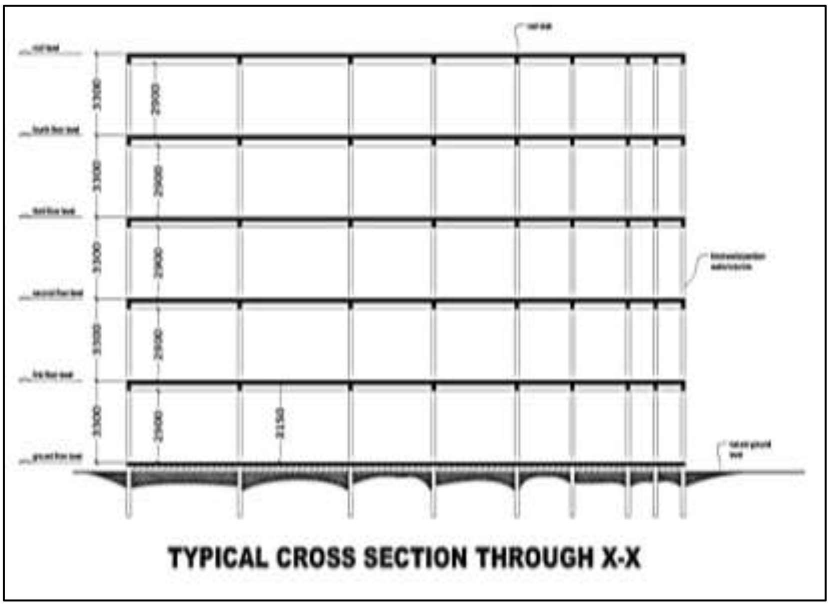

Figure 3: Typical Cross Section of Proposed Reinforced Concrete Structural Model

The model was developed using CSC Orion 18 Software, reinforced concrete design software. In general, eleven models were developed for different values of live loads and are as shown in table 1 below.

Table 1: Summary of Models

MODEL	LIVE(IMPOSED) LOAD
Q01	1.50KN/m^2
Q02	2.00KN/m^2
Q03	2.50KN/m^2
Q04	3.0KN/m^2
Q05	4.0KN/m^2
Q06	5.0KN/m^2
Q07	7.5KN/m^2
Q08	9.0KN/m^2
Q09	10.0KN/m^2
Q10	12.0KN/m^2
Q11	20.0KN/m^2

Simulation

Each model enumerated in table 1 above was simulated using CSC Orion Software.

Data Collation and Load Conversion Factor Computation and Collation

The loads, ultimate (factored) loads and service (unfactored) loads, on all 81 foundation columns were collated for each model and exported to Microsoft excel Software where the load conversion factor for each column was computed. The average load conversion factor for all 81 columns in a model was taken as load conversion factor for the model in consideration.

The load conversion factor is the ratio of the ultimate load to the service loads and the equation is as shown below.

$$LCF = \frac{Ultimate\ loads(F_{ULS})}{Service\ Loads(F_{SLS})}$$

Where LCF=load conversion factor,

F_{ULS} = loads computed at Ultimate limit state using load factor of 1.4 and 1.6 for dead and imposed loads respectively,

F_{SLS} = loads computed at serviceability limit state (i.e. loads at their actual state or unfactored loads).

RESULTS AND DISCUSSION

From the Data analysis the load conversion factors obtained for each model is summarised in Table 2 below.

Table 3: Load Conversion Factors for Various Live Loads and Pearson's Product Moment Correlation Coefficient

Models	Live load (kN/m²)	Load Conversion Factor (LCF)
Q01	1.50	1.418
Q02	2.00	1.419
Q03	2.50	1.423
Q04	3.00	1.427
Q05	4.00	1.434
Q06	5.00	1.441
Q07	7.50	1.455
Q08	9.00	1.462
Q09	10.00	1.472
Q10	12.00	1.474
Q11	20.00	1.499
Pearson's product	Pearson's r = +0.977	

moment correlation coefficient, r	

From Table 3, it will be observed that at 1.50kN/m², the Load Conversion Factor obtained was 1.418 and at a live load of 5.0kN/m², a Load Conversion Factor of 1.441 was obtained. These Load Conversion Factor values negate those proposed by Oyenuga (2001) i.e. Load conversion factor values of 1.46 and 1.49 at live load values of 1.50kN/m² and 5.0kN/m² respectively. The load conversion factor of 1.462 was obtained at live load of 9.0kN/m², though at live load value of 7.50kN/m², load conversion factor 1.455 was obtained. It is thus obvious that the Load Conversion Factor value of 1.46 was obtained at a live load value greater than 7.50kN/m² but less than 9.0kN/m² as against 1.50kN/m² detailed by Oyenuga (2001). However, the values of Load conversion factors obtained as detailed in Table 3 fall within the range specified in BS 5950 Part 1:2000 i.e. $1.40 \leq LCF \leq 1.50$.

At a live load of 10.0kN/m², load conversion factor of 1.474 was obtained while at a live load of 20.0kN/m², the highest value of live load employed so far, a load conversion factor of 1.499 was obtained. Practically, values of live loads will not exceed 20kN/m² thus it is certain that the range of values specified in BS 5950 part 1:2000 are realistic though not specific.

The relationship between the live load values adopted for this work and the Load Conversion Factors obtained was determined using Pearson's product moment correlation coefficient. The value of Pearson's r obtained was +0.977. This indicates a perfect positive relationship between the two items. This also implies that the value of load conversion factor is directly proportional to the live (imposed) load. As live load values increases, the load conversion factor also increases.

The Load Conversion Factors obtained were plotted against their corresponding live (imposed) loads. This is detailed in the graph in fig. 4

Figure 4: Graph showing Load Conversion Factor versus Live (Imposed) Load

The equation of a straight line graph is given by

$Y = mx + c$ -- equation 1

Where Y = values along the vertical axis,

m = slope or gradient

x = values along the horizontal axis

From the graph above, Y = load conversion factor and x = live (imposed) load values.

Slope, $m = (y_2-y_1)/(x_2-x_1)$ --------------------------------------- equation 2

From the graph above, if $x_2 = 9.0kN/m^2$, then $y_2 = 1.462$ and if $x_1 = 2.0kN/m^2$ then $y_1 = 1.4209$ and $c = 1.4092$. Therefore substituting these values in equation 2,

$m = 0.00587$

Thus equation 1 can be rewritten as

Load conversion factor (LCF) = 0.00587q_k +1.4092 ------- equation 3
Where q_k is the live (imposed) load.

Equation 3 can be employed to compute load conversion factor for a given live load value. However, it should be noted that the load factor applies to load combinations involving dead and live loads only with load factors of 1.4 for dead loads and 1.6 for imposed loads. Wind load nor its effects was not considered in this work.

CONCLUSION

From the above discussion, it was concluded that Load conversion factor values of 1.418, 1.419, 1.423,1.427, 1.434, 1.441, 1.455, 1.462, 1.472, 1.474 and 1.499 are applicable when live load values of live load values of 1.50kN/m^2, 2.0kN/m^2, 2.5kN/m^2, 3.0kN/m^2, 4.0kN/m^2, 5.0kN/m^2, 7.5kN/m^2, 9.0kN/m^2, 10.0kN/m^2, 12.0kN/m^2 and 20.0kN/m^2 are adopted. Alternatively, the equation, **LCF = 0.00587q_k + 1.4092** can be used to compute the load conversion factor for any given value of live (imposed) load. Also, the non-inclusion of load conversion factors in most major concrete and steel design codes and standards suggests it has not been considered a relevant design parameter.

This study therefore recommends the use of the load conversion factor values for the various corresponding live loads or the equation, **LCF = 0.00587q_k + 1.4092** derived in this study as an alternative. The inclusion of load conversion factors in structural design codes and standards is imperative considering its benefits in foundation design. Further research aimed at enhancing the application, relevance and reliability of load conversion factors is also encouraged as this will not only help in establishing a vast and robust data base on this design parameter but will greatly assist in enhancing its efficacy.

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