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Environmental Effect of Climate Change Pollutants Loading on Structural Steel Stresses

Ben U, Ngene [1#], Anthony N, Ede[1,##], Gideon O, Bamigboye [1,###], Kumar Prashant [2] and Imam Boulent [2]

[1] *Department of Civil Engineering, Covenant University, Ota, Ogun State, Nigeria.*
[2] *Department of Civil/Structural Engineering, University of Surrey, Guildford, United Kingdom.*
**Corresponding author*

[#]Orcid: 0000-0003-0675-7816, [##]Orcid: 0000-0002-4774-2365, [###]Orcid: 0000-0002-1976-2334

Abstract

Human activities on earth it is observed is having negative impact on the continuous existence of life on the planet. This is as a result of build-up of gases that tend to affect life and well-being of plants and animals including structures put in place to support them. Structural failure as a result of pollutant exposure does not occur unless where there is wrong design of the structure or the owner has not carried out routine maintenance. The effect of such loss on structure in place need to be further studied to engender better understanding of structural failure possibilities or its reliability. This work looked at the effect of gases such as SO_2 and humidity known as climate change gases in the air and their effect on steel structures, specifically bridges, in rural, urban and industrial locations. It was shown also that for these three types of locations, the moment resistance and shear resistance of structures overtime will decrease by 3% and 4.6% respectively. However, the deflection of the same structure will increase by 1% over the same time range. The implication will be an increase in the cost of design and construction as a result of increased thickness of steel structures and additional paint coating to reduce this negative effect.

Keywords: Moment resistance, Shear resistance, Deflection, Air pollution and Dose-response function.

INTRODUCTION

Human, it has been attributed is contributing heavily to global climate change through anthropogenic heat production and the emission of green-house gases [1]. The influence of such green-house gases and climate change is seen in the deterioration of existing structures such as buildings, cultural artefacts, coastal erosions and marine infrastructure damages [2]. Deterioration of materials due to air pollution come at high cost and the damage pose a long term effect on available infrastructure provided at high cost to the economy of nations [3]. The study estimated the deterioration of a steel bridge overtime using the dose-response function approaches. From this, the resistance of the structure overtime subject to such deterioration is estimated. Generally, the research looks at the factors that actually impact the service life existence and progress of deterioration of structures exposed to atmospheric weathering.

Structural failure due to pollutant loading or exposure can only take place in case of wrong design or due to lack of maintenance, hence generally are long term in nature. Understanding how air quality affects the corrosion of materials of construction especially Steel in unsheltered condition is therefore important to both the Structural and Environmental Engineers.

LITERATURE REVIEW

Impact of human activities on climate

Examples of attempts to control weather by human include seeding to augment precipitation or suppress hail or lightning or to clear fog or modify the structure and movement of hurricanes. Man may also influence climate inadvertently through his various actions and activities such as urbanization and industrialization, falling of trees, farming activities, draining of marshes or creation of artificial lake when rivers are dammed to provide water for various uses or for generation of hydroelectric power.

The greatest impact of man on climate is evident in urban areas. Here, the actions of man have such a tremendous impact on climate that the climate prevailing in urban areas is quite distinct in character from that in the surrounding rural areas [1].

Impact of climate on society

Changes in climate exert a lot of influence on human beings and the degree to which a particular environment is exposed to damage by climate reasons is termed its vulnerability. The human nature to adapt and withstand adverse climate impacts, however, is termed its resistance.

Studies have indicated that the ability of society to withstand adverse climate is not a linear function of its wealth or degree of development [4]. As observed by [5] energy, human health and comfort are more susceptible to be affected by climate than any other factor in the physical environment. Example, though ultraviolet rays help to form vitamin D in the skin and devitalize bacteria and germs, they can also cause sunburn and inflammation of the skin. In fact, ultraviolet rays coupled with intense heat can cause cataract of the eye. On the positive side also, fresh air, mild temperature, moderate relative humidity and sunshine also have healing value.

Economic activities such as in manufacturing industry, commerce, utilities, agriculture and animal husbandry, transport and communication are all influenced to varying degree by climate. These human economic activities can only be successfully pursued under right climate conditions [6-8].

Climate also influences the way a house is built and the type of dress humans wear and they vary from culture to culture and from climate zone to another. In this regard, [9] has noted the classification of the world into zones with respect to their clothing requirements to meet normal human body heat balance. Buildings location, materials choice, designs and method of air-conditioning of structure is affected by climate and weather conditions. In addition, however, the building structural safety and ability to carry the stresses arising from the prevailing climate during its anticipated lifetime must be guaranteed [7, 5].

Since construction activities take place in outdoor conditions, current weather condition with regard to rain, snow, high winds, and temperature extremes can affect it adversely. Estimates of the number of workable days for construction purposes are made using information on the weather variables [7].

Effect of climate change on climate parameters temperature

The world temperature is predicted to rise over the next century. This increase of some few degrees will be critical to many aspects of our lives and the health of ecosystems and agriculture [10]. By definition, the degree of hotness of a body as measured by a thermometer is its temperature. One critical aspect of temperature that affects large structures is seasonal changes. Large seasonal changes in temperature impose greater stress on buildings and structures. Generally, studies have shown that temperature have correlation with corrosion rates [11]. Temperature is noted to increase the rate of reaction, though for steel the rate decrease with increase in temperature and also dry the surface.

Rainfall

Corrosion of metals by rainfall is dependent on the pH of the rain, intensity, duration and amount. Though rainfall acidity is not easy to estimate, it is known from twentieth century measurements and records according to [12]. Coal ash present in the past century tended to make rainfall alkaline; hence a pH value of 5.5 is used for this work. The presence of SO_2 decreases the pH of rain, and also causes faster chemical attack. This can occur by the dissolution from rain acidity or attack of dry deposition of pollutant. As reported in [13,14] "hygroscopic SO_2 in the industrial atmosphere often lowers the pH of water, wets rust layer and dissolves the initial corrosion products of $\gamma - F_eooH$, and also promotes the phase transformation of $\gamma - F_eooH$ to amorphous ferric oxyhydroxide and $\alpha - F_eooH$". This transformation for weathering steel is known to takes place within the first three years of exposure.

Relative humidity

Relative humidity is one of the climate parameters included in most of the established dose-response functions. It defines the percentage of vapour density to saturation vapour density at any given time. For relative humidity, the transformed variable is $Rh_{60} = (Rh - 60)$ when $Rh > 60$; otherwise 0 is used in the dose-response function [15].

As indicated by [10] cycles of relative humidity causes crystallization and dissolution, which exert stress on structural materials in which weathering salts are present, [16,17] concluded that at high relative humidity, SO_2 might form ferrous sulphate, which would attract water and be dissolved on steel surfaces, thereby accelerating the corrosion with little contribution from NO_2.

Time of wetness

For weathering steel, the time of wetness (TOW) may be interchangeably used with relative humidity. This is because steel show high critical humidity for corrosion process [18].

Bartonj and Cherny [19] has shown that there is a correlation existing between corrosion under absorbed water films and the amount of SO_2 absorbed by the films over a period equal to TOW as in

$$f_{dry} = C[SO_2]^A.TOW^B$$

The power functions take into consideration the nonlinearity of this expression regarding both SO_2 and TOW.

The deposition of atmospheric pollutants such as sulphate dioxide on structures such as buildings and bridges is influenced by time of wetness or humid condition. Water soluble gases such as SO_2 and other particulate matters can be deposited more effectively under humid environment than in dry condition.[20] concluded that when metal atoms are exposed to an environment containing water molecule they can give up electrons, becoming themselves positively charged ions-provided an electrical circuit can be completed

Factors affecting air quality

Chemical composition of the atmosphere is of great importance to the corrosion process because of their thermodynamic and kinetic effect on corroding material. Mellanby [21] observed that the most important pollutant that affects structural materials are sulphur dioxide and oxides of nitrogen and their oxidation products, together with chlorides and particulate matter. Ozone was also considered as its presence affects the quality of the air.

Sulphur dioxide

Emission of this substance arises from man's activities such as in different fuel use. The observed decline in United Kingdom of SO_2 emissions since 1980 has been attributed to equal proportions to energy economies, reduction in sulphur content of fuels, changes in fuel use patterns (e.g. to natural gas) and industrial modernisation.

Results of site monitoring have revealed that over the past 30 years, the decrease in urban SO_2 concentrations have clearly arisen primarily from the decrease in domestic and industrial/commercial emissions [21].

$$SO_2 + NO_2 \rightarrow SO_3 + NO$$

Smoke

While the current United Kingdom average smoke concentration of urban annual means is $17\mu gm^{-3}$, that of central London is put at $25 - 35\mu gm^{-3}$. This represent a fall from the 1960 average of 140 μgm^{-3} with some areas as high as $350\mu gm^{-3}$. The consequence is that motor, especially, diesel vehicles are often the predominant contributor to smoke concentration.

Oxides of nitrogen

Estimates from Warren Spring laboratory [22] indicates that United Kingdom annual emission of NO_x was almost flat from 1905 to 1945 but increased by a factor of 2 to date. This increase is attributed to increased oil consumption by the transport sector. Peak hourly concentration are affected by meteorological conditions and for long it is put at an average of $60 - 80\mu gm^{-3}$ for $2NO_2$ and $40 - 65\mu gm^{-3}$ for NO

$$2NO + O_2 \rightarrow 2NO_2$$

$$2NO + O_2 \rightarrow 2NO_2 - O_2$$

Ozone

These are not considered as primary pollutants. It is produced in high concentrations in the stratosphere by UV irradiation and transported into the free troposphere to supplement ozone produced there photo chemically [22]. For the United Kingdom, the average annual concentration in urban areas range from $20 - 40\mu gm^{-3}$ while for rural area it is $40 - 60\mu gm^{-3}$. For reason of area of primary production, ozone depends on meteorological variation for its dispersal. Apart from that, it also depends on sufficient sunlight and favourable air mass trajectory to transport it from source to its receptors. Hydrocarbons in the atmosphere can be oxidized by ozone as follows:

$$RH + O_3 \rightarrow R'CHO + O_2$$

Carbon dioxide

This is not considered as pollutant gas. However, its presence in the air does add to the acidity of rain water and thereby cause some degradation to limestone and concrete. Combustion of fossil fuels has caused a considerable increase in atmosphere concentration of CO_2 from approximately 290ppm in 1870 to 340 ppm in 1985 [12]. As a result, attacks by CO_2 on calcareous stones proceeds more rapidly because the CO_2 concentration increase leading to a higher partial pressure and more decay and directly because of the low pH [22].

Dose response

Literally, this is the function that determines the impact of the application of a certain quantity of a substance on the receptor. Environmental impacts of dose response functions are liberally considered as measured data are globally used to predict equation on local scale. In this regard, dose-response functions are geographically transferable.

Environmental parameters:

Dose-response functions include such climate data as temperature (T), relative air humidity (Rh), gaseous emissions in the air (SO_2, NO_2 and O_3) and amount of precipitation. Difficulty in obtaining time of wetness (TOW) resulted in its exclusion [23].

Though polluting gaseous emissions such as SO_2, $NO_2$and O_3 were included in the statistical analysis, the negative correlation between $NO_2$and O_3 (NO_2 level is low in rural and high in urban atmosphere, while O_3 is the reverse) is observed. Note that it is difficult to identify the effect of NO_2 and O_3 separately.

Estimation of corrosion losses

Weathering steel, an alloy of Nickel, Copper etc. has the dose-response function as shown for outdoor application [23].

$$In(ML) = 3.54 + 0.33In(t) + 0.13In(SO_2) + 0.020Rh + 0.059(T - 10)\ for\ T \leq 10°\mathrm{C}$$

and

$$In(ML) = 3.54 + 0.33In(t) + 0.13In(SO_2) + 0.020Rh + 0.036(T - 10)\ for\ T > 10°\mathrm{C}$$

where t = time in years, T = Air temperature, Rh = Relative humidity (%), $[SO_2] = SO_2$ concentration (μgm^{-3}), $[NO_2] = NO_2$ concentration (μgm^{-3}), $O_3 = O_3$concentration (μgm^{-3}), Rain = Quantity of Rainfall (mm), $[H^+] = H^+$concentration $(mg/l)$and [CL-] = CL- concentration (mg/l).

Impact pathway

The [24] project identified metals (steel) as one of the pathways of acidic emissions and precursors of photo-oxidants effect on materials. The impact pathway follows the following routes: discoloration, materials loss and structural failure. Structural failure from pollutant exposure is more noticeable where there is fundamental flaw in design or the property does not have good routine maintenance programme.

Failure probability of corroded structures

According to [25], corrosion has many variables with uncertain nature. For this reason, the use of probabilistic model to describe the expected corrosion of structures is appropriate and desirable in reliability assessment. The reliability (probability of survival or no failure) of a structure is defined as

$$P_s = 1 - P_f$$

Reliability and failure probability

The limit state design process is defined by the principle of structural reliability, [26]. Two types of limit states identified include Ultimate limit state and Serviceability limit state.

Total failure of a structure by any mechanism (fracture, buckling, overturning etc.) is considered to be failure under Ultimate limit state. Other forms of limit state may however cause a structure not to be fit for purpose. The function $g(x)$ describes the limit state as

$g(x) > 0$ limit state is satisfied (safe set)

$g(x) < 0$ failure occurs (unsafe set)

$g(x) \geq 0$ failure surface

with x a vector of statistical variable which takes into account uncertainties.

$$\text{and} P_f = P(g(x) < 0) = P(R - S < 0)$$

From [27] under normal distribution, the probability of failure $P_f$of a structure is calculated from

$$P_f = \frac{\emptyset[-\mu_R - \mu_C]}{\sqrt{\sigma_R^2 + \sigma_S^2}} = \emptyset[-\beta]$$

Where $\mu_R$and μ_c are means and

σ_R and $\sigma_S$are standard deviation of the load and resistance variables and $P_f$is the cumulative density function of the standard normal distribution.

but reliability index $[\beta]$can be expressed as

$$\beta = -\emptyset^{-1}(P_f)$$

In order to solve the probability of failure function above, the Monte Carlo simulation or analytical methods (First Order Reliability Method) is employed.

Code requirement for reliability

As earlier noted, the product of failure probability and cost of failure defines the risk level or target level of reliability. According to [28] uncertainties associated with modelling of deteriorating structures have strong influence on management decisions, such as when to inspect and scheduling of maintenance and repair actions. In this regard structural elements that are frequently inspected, show warning signs if failure is approaching or can redistribute its loads to other elements and hence less likely to cause loss of life at failure. ISO 2394 [26] suggested for serviceability limit state a target level of reliability, $\beta = 0$ for reversible and $\beta = 1.5$ for irreversible limit states.

Impact of location of structure and corrosion

Steel structures are not significantly affected by rural corrosion since high ozone level governs. However, urban and marine corrosions are significant since sulphate and chloride emission prevails in both environments. Kayer [29] noted that bearing and shear prevail in high levels of corrosion as their resistance is based on Webs (thin member) susceptible to thickness loss effect. In the same vein, compression members are more sensitive to corrosion since it is subject to buckling. Adebiyi et al., [30] in his predictive model for evaluating corrosion rate of mild steel in six environments concluded that the mean corrosion rate using theoretical model varied from 0.12 cm/yr (for borehole water) to 0.55 cm/yr (for H_2S0_4).

In the works of [31], on the effects of time dependent loads and corrosion on bridge reliability, it was determined that failure due to shear force is a more immediate threat to a structure than due to moments.

Surveswaran *et al.,* [32] examined the effect of corrosion penetration in I-girder structure reliability. The result indicates an adverse rate of corrosion for the bottom $1/4$ of the web and flange. Corrosion attack was noted for top and bottom surfaces of flanges.

Lateral torsional buckling was determined as the most critical failure mode affecting corroded beam; followed by shear which affect the material loss of the bottom quarter of web and finally moment as compression flange is less significant.

METHOD AND MATERIALS

Methodology

The impact of climate change on built infrastructure analysis is achieved in two stages of examining the appropriate Dose-Response function for pollutants and evaluating their impact on a railway bridge structure.

In stage one, the mean and standard deviation of the pollutant data are obtained. From the mean, a dose-response value of the annual material loss is calculated for weathering steel. Evaluating the impact of climate parameters in the second stage involves probabilistic evaluation of the time to failure of various stages of corrosion on simply supported railway bridge structure using the moment and shear resistance and deflection checks.

Data

The data for this work were obtained from the work of [12] on estimates of recession rate of limestone facades in London over a millennium.

This inhomogeneous data involve climate and pollutant parameters which have historic data, non-instrument and instrument data and future projections.

The record which represents climate around London region (Central England Temperature

Record) can be extended to Guildford which has similar geographic and meteorological characteristics. Key to the merger of earlier historical records with instrument data as

observed by [33] was the high regression coefficient $R^2\ of\ 0.73$ between the data.

Theory of analysis

EFFECT OF ANALYSIS ON MATERIALS

Dose-response function and estimation of material loss

In unsheltered condition, wet deposition (through rain) of SO_2 is the most important pollutant parameter for weathering steel and zinc. Several researchers have worked on the appropriate dose-response functions that will possibly capture the adverse effect of climate and pollutant parameters on built structures, however, dose-response function for the calculation of a year corrosion loss for carbon steel based on [34] is

$$r_{corr} = 1.77[SO_2]^{0.52}.exp^{(0.020Rh+f_{st})} + 0.102[CL^-]^{0.62}.exp^{(0.033Rh+0.040T)}$$

where $f_{st} = 0.150(T-10) when\ T \leq 10°\text{C}, otherwise - 0.054(T-10), r_{corr} =$ first year corrosion rate of carbon steel in $\mu m/year$.

The Dose-Response function above is used to determine the thickness loss from the surface of a corroded steel structure which depends on the parameters of interest.

BS EN ISO 9223:2012

ISO 9223 is the code for the classification, determination and estimation of corrosion of metals. Based on comparative estimation of the various dose-response function thickness losses, the function for this code was chosen for the analysis.

This is because it gives the result close to the average thickness loss calculated in this work from other functions. The second reason for the choice of the dose-response function for the analysis is because of the critical influence of the parameters in the corrosion rate of metals.

Determination of corrosion rate

Determination of the corrosion rate is based on one year exposure of metals and the measurement of the corrosion of the standard specimens according to [34]. From this test, the numerical values of the first year corrosion rate of different metals under various corrosivity categories are stated.

Estimation of corrosion rate

The estimation of the one year corrosion losses for carbon steel is based on the dose-response function as stated below:

$$r_{corr} = 1.77[SO_2]^{0.52}.exp^{(0.020Rh+f_{st})} + 0.102[CL^-]^{0.62}.exp^{(0.033Rh+0.040T)}$$

where$f_{st} = 0.150(T-10) when\ T \leq 10°\text{C}, otherwise -$

$0.054(T-10)$, N =128, $R^2 = 0.85$ and $r_{corr} =$ first year corrosion rate of carbon steel in $\mu m/year$.

Effect of Corrosion (thickness) Loss on Steel Bridge

Design of simply supported railway bridge

Using the principle of limit state, a design of beam section is made with the ultimate limit state and checked for deflection using the serviceability limit state.

Determination of loading

The combination of action is determined according to the expression in equation 6.10 [26]

$$\sum_{j>1} \gamma_{G,j} G_{k,j} + \gamma_p P + \gamma_{Q,1} Q_{k,1} + \sum_{i>1} \gamma_{Q,i} \omega_{0,i} Q_{k,1}$$

Where γ_G and γ_Q, represents the partial safety factors with modelling uncertainty

G_k, the characteristic value of permanent action

Q_k, the characteristic value of variable action

P, the characteristic value of a prestressing force where applicable

ω_0, is the combination factor for variable action

Calculation of moment and shear resistance

These are obtained using the elastic method for simply supported structure as

Moment, $M = w\,L^2/8$ and the moment of resistance for the main girder is calculated using $M_D = M_R/\gamma_m \gamma_{f3}$ according to clause 9.9.1.2 of [35] part 3

and

Shear Force, $V = w\,L/2$ while the shear resistance is given as

$V_D = \left[t_w\,(d_w - h_h)/\gamma_m \gamma_{f3}\right]\tau_1$ clause 9.9.2.2 [35] part 3

here w is the load in KN/m and L is the span length, M_D is the bending resistance, M_R is the limiting moment of resistance, γ_m is the safety factor and γ_{f3} is partial factor on characteristic yield stress.

For the shear resistance V_D is the shear resistance of the web panel, t_w the thickness of the web, d_w is the overall depth of the girder, h_h height of any opening, γ_m and γ_{f3} as defined above and τ_1 is the limiting shear strength of the web panel.

Verification of serviceability limit state of deflection

The check is made to verify the damage that will likely adversely affect the durability of the structure. Bridges structures are designed so that the deflections under load do not bear on any required clearances.

The combination actions for this check are expressed as:

$$\sum_{j>1} G_{k,j} + P + Q_{k,1} + \sum_{i>1} \omega_{0,i} Q_{k,1}$$

where variables are as earlier defined.

For the verification of deflection, the equation is

$\delta = 5wL^4 x\, 10^{12}/384EI(mm) < L/800$(UIC Code 776-2R, 2^{nd} ed 2009)

Where δ is the deflection (mm),

w = Total Load on the structure in (kN)

L = Bridge span in (mm)

E = young's modulus (N/mm^2)

I = Second moment of area (mm^4).

The effect of cross girder section was not considered in the determination of the deflection of the main girder section.

RESULTS AND DISCUSSIONS

Estimation of dose-response functions

An average dose-response function was determined as in table 1 below and used in the calculation of the thickness loss in the work. The average function is a plot of the mean of the highest and lowest at all the points of the one year functions. Different results obtained for different dose-response may be attributed to the nature of analysis and the parameters input used in various analysis. For example, while some used SO_2, Relative Humidity and Temperature only in their formulation others added the effect of O_3, pH and particulate matter in the equat

Table 1: Mass Loss based on an average dose-response function .

Time(t)	Year	PM_{10}	SO_2	NO_2	O_3	HNO_3	Temp.	pH	RH	Rain	Avg. Dose-Respone
Years		(µg)m^{-3}					(^{0}C)		(%)	(mm)	(µm)
1	2010	30	17	40	40	1.15	11.8	5.2	72	582	26.54
20	2030	15	15	20	30	0.71	12.3	5.5	71	590	68.75
40	2050	14	14	20	30	0.73	12.9	5.5	71	604	94.44
60	2070	13	13	20	30	0.77	14.4	5.5	70	574	112.93
80	2090	12	12	20	30	0.73	13.4	5.5	68	551	126.41

Discussion of results

The following regression function was based on the curves generated from excel for the average dose-response:

Ave. Dose-Response with regression function, $y = 2503.2In(x) - 19002$ and error coefficient $R^2 = 0.9525$

From the outputs of the function, it is observed that the function closest to the average value is the ISO 9223 function hence the use in the work for the calculation of the thickness loss.

Analysis of the pollutants

According to ISO 9223 categorization, the table 2 below shows the values of the thickness loss with their classification.

Table 2: Classification of mass loss according to ISO standard

Year	ISO 9223	ISO Classification	
	(µm)	Range	Category
2010	29.58	25<ML<50	C3
2030	56.02	80<ML<200	C5
2050	80.72	80<ML<200	C5
2070	102.20	80<ML<200	C5
2090	123.09	80<ML<200	C5

Time variation of parameters

Each of the parameters is analysed for the effect of change in value on thickness loss. A change in percentage made an increase in the value of each of the parameters. This indicates that with an increase each year of the parameters the thickness loss tends to increase

Table 3: Effect of % age change on parameters relative to 2050 values

%age change	2050 Refernce year parameters							ISO 9223
	$S0_2$ (µg)m^{-3}	Thickness Loss (µm)	**Temp. (^{o}C)**	Thickness Loss (µm)	**RH (%)**	Thickness Loss (µm)	ISO 9223 (µm)	DRF1(µm)
-20	11.2	21.99	10.32	28.39	56.8	18.59	29.58	29.58
-10	12.6	23.38	11.61	26.48	63.9	21.43	26.44	56.02
0	14	24.70	12.9	24.70	71	24.70	24.70	80.72
10	15.4	25.95	14.19	23.04	78.1	28.47	21.48	102.20
20	16.8	27.15	15.48	21.49	85.2	32.81	20.90	123.10

Discussion

From the table 3 above, increase in temperature does not increase thickness loss while for other parameters, sulphur dioxide and relative humidity, increases thickness loss with their increase. Example, from the table, a 10% increase in SO_2 will cause a 5% increase in thickness loss, which for a 20mm thick web will give rise to a reduction of 1mm thickness. A 10% increase in temperature on the other hand will cause 7% decrease in thickness loss. Increase in relative humidity by 10% will cause a 15% increase in thickness loss. It is therefore observed that increase in relative humidity will increase the amount of water vapour hence dissolved SO_2 and other gases and also increase in the time of wetness of corrosive materials on the structure.

Spatial variation of parameters

In this regard, it is observed that location affects the rate of loss of materials from steel exposed to the climate change. Materials exposed to the rural area is least affected while those in industrial environment is most affected as seen in figures 1-3 below. Table 4-6 below shows the use of the ISO 9223 dose-response function to obtain the thickness losses over time for rural, urban and industrial environments. To obtain these values, the SO_2 is varied for the rural, urban and industrial areas while the temperature and relative humidity is kept constant. A plot of the thickness loss against time for various environments gives the rate of corrosion.

Table 4: Rural values of $SO_2(2 < SO_2<15)$

Time Year	**Year**	**PM_{10}** (µg)m^{-3}	**$S0_2$**	**$N0_2$**	**O_3**	**$HN0_3$**	**Temp.** (^{0}C)	**pH**	**RH** (%)	**Rain** (mm)	ISO 9223 (µm)
1	2010	30	17	40	40	1.15	11.8	5.2	72	582	29.58
20	2030	15	15	20	30	0.71	12.3	5.5	71	590	56.02
40	2050	14	14	20	30	0.73	12.9	5.5	71	604	80.72
60	2070	13	13	20	30	0.77	14.4	5.5	70	574	102.20
80	2090	12	12	20	30	0.73	13.4	5.5	68	551	123.09

Table 5: Urban values of $SO_2(5<SO_2<100)$

Time	**Year**	**PM$_{10}$**	**S0$_2$**	**N0$_2$**	**O$_3$**	**HN0$_3$**	**Temp.**	**pH**	**RH**	**Rain**	ISO 9223	ISO 9223
Year		(μg)m^{-3}					(^{0}C)		(%)	(mm)	(μm)	(μm)
1	2010	30	78	40	40	1.15	11.8	5.2	72	582	65.32	65.32
20	2030	15	69	20	30	0.71	12.3	5.5	71	590	58.47	123.79
40	2050	14	64	20	30	0.73	12.9	5.5	71	604	54.43	178.22
60	2070	13	60	20	30	0.77	14.4	5.5	70	574	47.58	225.80
80	2090	12	55	20	30	0.73	13.4	5.5	68	551	46.12	271.92

Table 6: Industrial values of SO$_2$(50< SO$_2$<400)

Time	**Year**	**PM$_{10}$**	**S0$_2$**	**N0$_2$**	**O$_3$**	**HN0$_3$**	**Temp.**	**pH**	**RH**	**Rain**	ISO 9223	ISO 9223
Year		(μg)m^{-3}					(^{0}C)		(%)	(mm)	(μm)	(μm)
1	2010	30	360	40	40	1.15	11.8	5.2	72	582	144.68	144.68
20	2030	15	315	20	30	0.71	12.3	5.5	71	590	128.78	273.47
40	2050	14	295	20	30	0.73	12.9	5.5	71	604	120.49	393.96
60	2070	13	270	20	30	0.77	14.4	5.5	70	574	104.02	497.98
80	2090	12	250	20	30	0.73	13.4	5.5	68	551	101.35	599.32

Discussion

From the tables 4,5 and 6, it is shown that sulphur dioxide corrosion is much high for industrial area than in rural environment. The effect is therefore a higher thickness loss in the industrial area than in the rural. The rate of corrosion is shown to be 1.17 um/a, 2.58 um/a and $5.68\, um/a$for rural, urban and industrial areas respectively. This shows that SO_2 corrosion rate compared for rural to industrial is approximately five times while urban compared to industrial and rural compared to urban rate is slightly above two times for each.

Depth of corrosion

Steel corrosion rate with time for outdoor exposure is not constant. From ISO 9224, it is shown to decrease with exposure by the relation:

$$D = r_{corrosion} * t^b$$

Where t is the exposure time in years, $r_{corrosion}$ is the rate in the first year expressed in $um/a$and b is the metal-environment-time exponent, which for carbon steel is 0.026.

The following expressions show the $r_{corrosion}$ used for the determination of the depth of corrosion for the various environments viz rural, urban and industrial.

For the rural area, $r_{corrosion}(2 < SO_2 < 15) = 3259.8In(X) - 2473$

Urban environment had, $r_{corrosion}(5 < SO_2 < 100) = 5281.9In(X) - 40104$

and the industrial area has,$r_{corrosion}(50 < SO_2 < 400) = 11623In(X) - 88252$

Effect of climate change on structures

Impact on a railway bridge structure

The following are the analysis done to calculate the effect of material loss on the railway bridge structure. The worked example is of a twin-track bridge spanning 36m as in SCI Publication P318, [36]. The bridge is square at its ends and the slab is wholly on top of the cross girders.

Design parameters

The design is for 2 standard gauge tracks on straight alignment, track speed up to 160 km/h. Access walkway is provided on one side of the track and a continuous position of safety on the other side. The track is located with approximately 100 mm clearance between the outer edges of the walkway and the inner edges of the top flange, to allow for possible future realignment of the track.

Heavy traffic, 27 × 106 tonnes/annum was used for the analysis.

Grade S355 steel and grade C40 reinforced concrete was used.

The plot of the effect of thickness loss on moment resistance, shear resistance and deflection are shown in the figures 1-3 below.

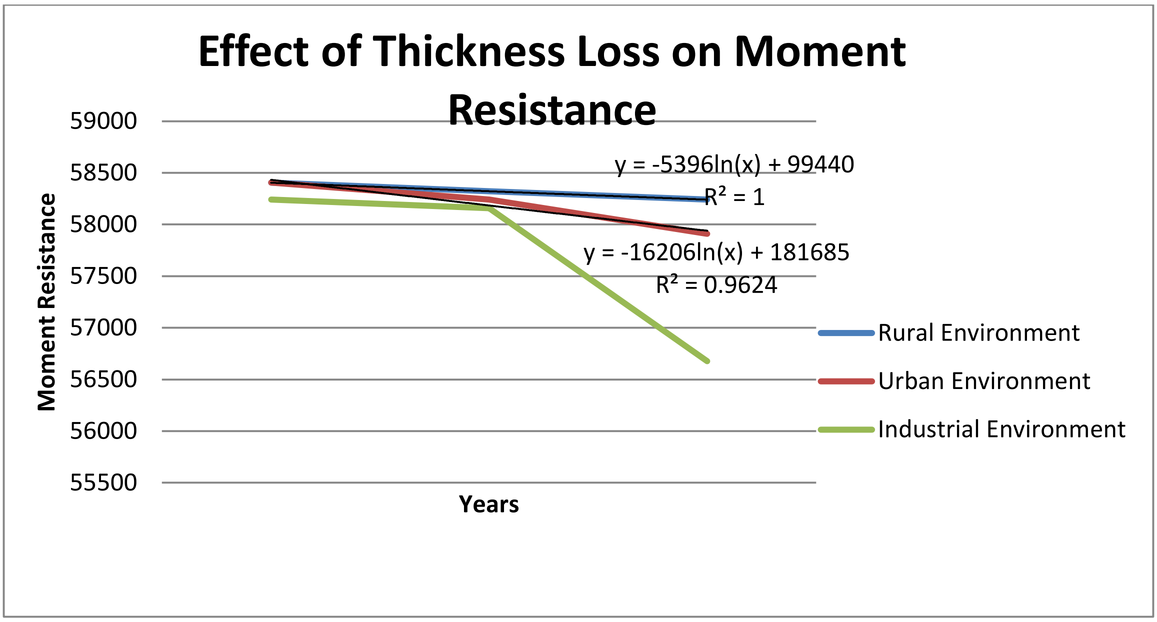

Figure 1: Effect of thickness loss on moment resistance of bridge girder

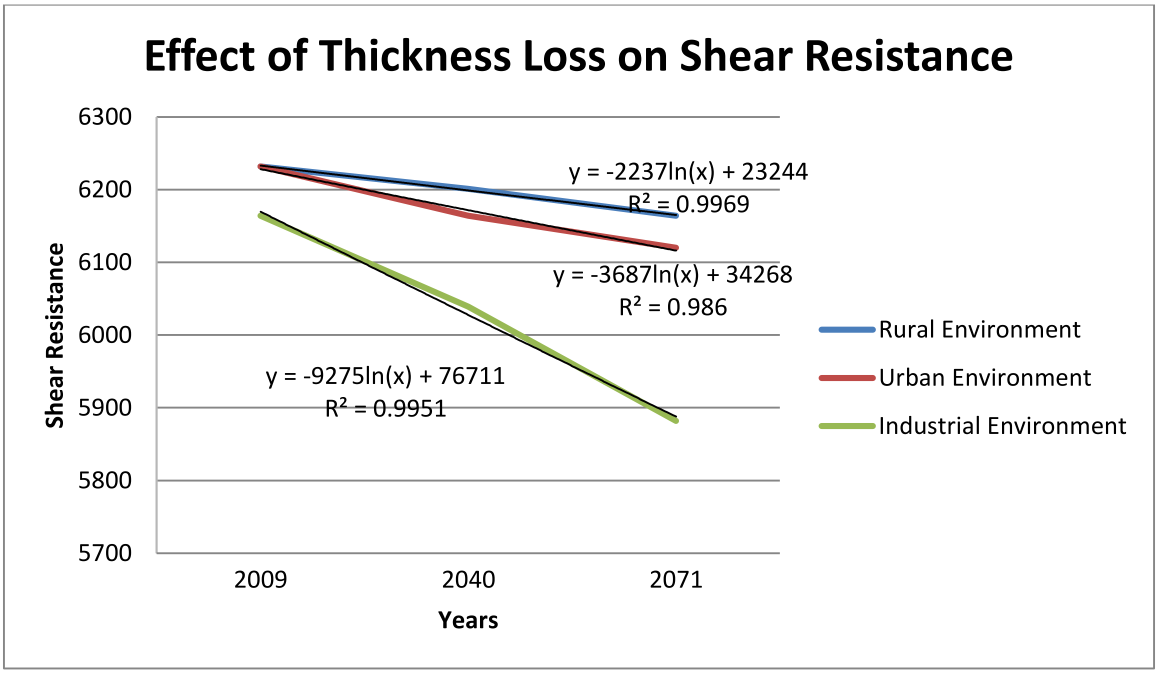

Figure 2: Effect of thickness loss on shear resistance of bridge girder

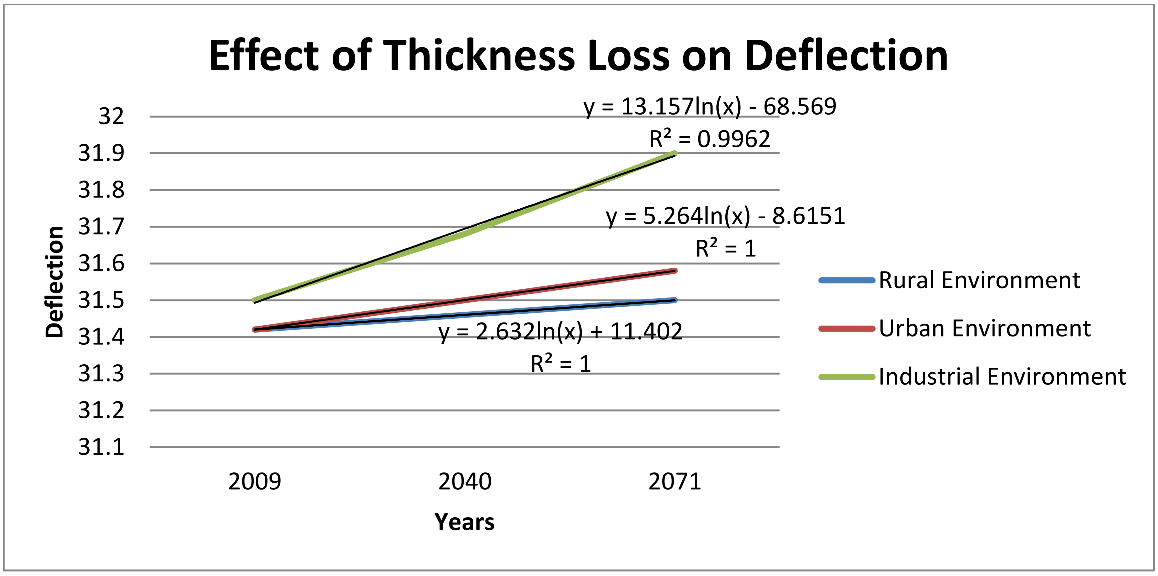

Figure 3: Effect of thickness loss on deflection of bridge girder

Discussion

From the results reflected in the figures 1-3 above, thickness loss due to corrosion of steel structure caused by climate change has long term impact on the effectiveness of the structure to carry the design load.

It is obvious that the moment resistance decreases with time depending on the location of the structure. The analysis shows that the rate of decrease of moment resistance is 0.3% for rural area, 0.9% for urban area and 3% for industrial environment. For industrial locations, the rate of fall of moment resistance increases faster after 40years, a period of stable decrease as the top flange deteriorate.

The shear resistance fall is sharper for all environments, as the web is the load carrying member in the girder with small thickness. For the rural area the decrease in shear resistance is slightly above 1%, while the urban and industrial area is 1.8% and 4.6% respectively. This will justify the need to increase the thickness of the web and reduce the spacing of the stiffeners.

From figure 3 the deflection of the girder increases with time and location of the structure. Deflection is more with industrial location and least in rural environment as the analysis has shown 0.18% for rural area over time, 0.36% for urban environment and 0.89% for industrial location.

The second stage involves the check of the effect of thickness loss on moment resistance, shear resistance and deflection of the analyzed bridge as shown. Results obtained indicate that while the moment and shear force resistance of the structure is decreasing with thickness loss over time, deflection is increasing.

CONCLUSIONS

Various building materials affected by climate change were identified with their impact noted. The impact of climate change was observed to be more noticeable in the urban areas than in the rural setting due to the effect of industrial gases and other anthropogenic effect in the atmosphere.

From the result obtained in first stage, a check on the effect of thickness loss on moment resistance, shear resistance and deflection of the analysed bridge is conducted. Results obtained indicate that while the moment and shear force resistance of the structure is decreasing with thickness loss, deflection is increasing.

The result of the parametric analysis has shown that the presence of SO_2, a pollutant resulting from industrial activities and high relative humidity based on climate factors affects thickness loss. In this regard a 10% increase in the two factors will cause a 5% increase in thickness loss for SO_2 and 15% thickness loss for relative humidity.

The moment resistance for the designed structure shows a decrease of 0.3% for rural area, 0.9% for urban area and 3% for industrial environment. Shear resistance decrease is 1.1% for rural, 1.8% for urban and 4.6% for industrial areas.

Finally, it is hoped that a further work may look at the fatigue behaviour of the structure under the same condition.

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