Durability of Cold Formed Steel Structures used in residential and industrial construction

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ABSTRACT

Cold formed steel is an attractive alternative to traditional construction materials such as masonry and concrete owing to the advantages such as easy fabrication, light weight, reusability of the material and higher level of recyclability. Cold formed steel buildings are also appreciated for better insulation and lower energy consumption during operation. However, durability of the steel was the main concern for stakeholders as corrosive conditions can damage the material and deteriorate the condition of the building. Therefore, it is important to understand the durability of cold formed steel coated with zinc and zinc alloys. In this study, experimental data related to durability studies available in literature was collected and presented through an analysis. The data obtained from literature indicate that if the building envelop was designed appropriately to protect the steel from exposure conditions, the steel can fulfil the expected service life of residential buildings independent of environmental and climatic conditions. Therefore, this study helps to alleviate concerns regarding durability of cold formed steel in residential construction.

KEYWORDS: *cold formed steel, durability, design life, corrosion, zinc alloys*

1 INTRODUCTION

Buildings are designed for a service life as per the recommendations of BS EN 1991 (BSI, 2003). It is expected that a building will function without any deterioration during its service life. However, the service life can be compromised due to exposure conditions of the buildings and the type of materials used. In recent years, cold formed steel is gaining popularity in the construction sector as an alternative construction material to concrete and timber. Lightness of the material, high strength to weight ratio, ability to mass produce, easiness in working at the site and economy in transportation are considered to be the major advantages of the material (Yu, 1999). Cold-formed steel (CFS) members are made using graded structurally sound steel sheets that are rolled by a forming machine to form the required shapes without the use of heat (unlike hot-rolled steel). Several steel thicknesses are available to serve a wide range of structural and nonstructural uses. The thickness of the members can range from 0.01 mm to 7 mm. Typical cold formed sections that are used in structural and non-structural applications are shown in Figure 1. Cold-formed steel (CFS) buildings have dominated the market for internal, non-loadbearing

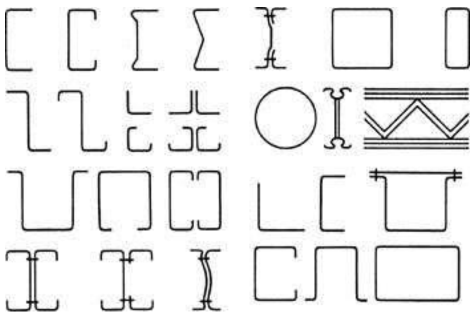

Figure 1: Typical cold formed steel sections

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partition walls in commercial construction because they are lightweight, extremely robust, noncombustible, and rather simple to install. However, the most worried factor about steel is its durability against corrosive conditions when it considered as a load carrying structural element.

Cold formed steel in residential applications is not new to Sri Lanka. Cold formed steel sections have been used in roof construction for more than 40 years. However, it has not been used as a major structural material in construction in the Sri Lankan context till recently. Steel has been used in house construction since 1920s and there has been a surge in steel housing after the world war 2 in the UK (Harrison, 1987). However, these housing units did not meet the thermal insulation requirements of 21st century and many structures used hot rolled steel. In terms of steel protection, most of these structures used paints as a corrosion protection layer. The cold formed steel used in residential construction assembled using several types of sections that can be rolled from the commercially available rolling machines. C section, lipped C section are commonly used in wall frames and floor joists (Figure 2 and Figure 3). Use of Z section in addition to C, lipped C can be found for roof construction (Lawson et al., 2010).

Figure 2: Wall frames in a cold formed steel building

Figure 3: Floor joists in the building

Cold formed steel (CFS) construction is carried out using three common methods such as stick built (fabricating wall frames and floor/roof truss at the site using CFS elements), constructing using panel (panels constructed at the factory and completed with insulating layers and external boards moved to site for assembly) and complete modular unit ready to install. The fabrication of the panels and elements carried out using one or combination of bolting, self-drilling, self-tapping screws, riveting, welding etc. Self-drilling or bolting are more preferred as they offer the material a chance to be re-used after the completion of the service life.

Although steel provides several advantages such as easy construction, higher level of re-usability or recyclability, corrosion in steel considered to be a greater threat to the structure despite many advantages. There are several steel protection methods that have been used to enhance the durability of the material. They are anodizing, galvanizing, powder coating, painting, epoxy coating and duplex coating. Estimated lifetime of different types of coating are given in Table 1. The oldest, basic and cheapest protection method is anticorrosive paints to protect the steel. Due to abrasion or from aging the paint coating can be damaged and corrosion can occur. Although paints are still used for hot rolled steel, it is uncommon to use paints in cold formed steel.

Table 1. Estimated lifetime of different coatings

Types of steel Coatings	Estimated life to first maintenance
Anodizing	~ 10-20 years
Galvanizing	~ 30 to 170 years
Powder Coating	~ 40 years
Paint coating	~ 10-20 years
Epoxy Coating	~ 40 years
Duplex coating	~ 90–150 years

The commonly used coating is galvanization for CFS. Steel profiles conforming to coating as described in BS EN 10346 (BSI, 2006) in the UK (EN 10346 in EU) and AS 1397(Standards Australia, 2021) in Australia are used in the respective countries. In both codes, the zinc coated elements should be dipped inside 99% pure zinc to achieve a coating defined from Z100 to Z 600. Z indicates the zinc coating and 100, 200, 275 to 600 indicate the weight of the coating. In the UK, Z275 is a preferred zinc coating for CFS residential buildings. Similar observations are observed in Australia as well. Sri Lanka adopting Eurocode may conform to similar coating requirements. In 1972, Bethlehem Steel Corporation developed a "Galvalume" steel coating (Coni et al., 2009). This coating consisted of 55% Aluminum, 43.5% Zinc and 1.5% silicon. It was observed that Galvalume steel demonstrate comparability better durability in coastal and marine environment and ability to resist heat better than zinc coated steel (Coni et al., 2009).

AZ 150 (Galvalume coating of 150 g/m^2) can give a similar coating thickness of Z275 (zinc coating of 275 g/m^2). Therefore, there is a greater interest to use AZ 150 steel instead of Z275 in construction industry due to enhance properties of the Galvalume coated steel.

Like painting, powder coating and epoxy coating provide protection to steel from corrosive conditions. These methods do not involve any sacrificial material similar to zinc in protecting steel. However, duplex coating involves an additional painting or powder coating applied on top of galvanized surface. Although it provides better protection than galvanized steel, it may not be an economical choice. Several research studies have been carried out to investigate the durability of different protection methods used in hot rolled and cold formed steel. This study aims to compare the data available from literature on durability of cold formed steel to recommend an appropriate coating method that could be used in the Sri Lanka condition for various climatic conditions.

2 COLD FORMED STEEL CONSTRUCTION IN SRI LANKA

CFS has been used for more than 40 years in roof and temporary construction in Sri Lanka. However, it is relatively new to the construction industry as a structural load bearing element for entire residential construction as shown in Figure 2.

2.1 Ground Floor

Several methods can be adopted to construct the ground floor. Depending on the bearing capacity of the soil, ground floor can be constructed as a slab on grade as shown in Figure 4 or a suspended concrete slab on pad footing as shown in Figure 5. As it is required to install load bearing steel frames on the slab using anchored connectors, a full concrete slab provides more flexibility to the constructing team. However, using concrete slab can increase the energy dissipation through the slabs. Alternatively, a suspended timber composite slab supported by CFS trusses can be used to achieve better insulation.

Figure 4: Slab on Grade (Kampert, 2021)

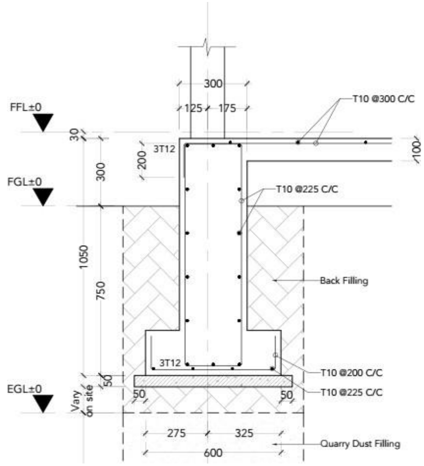

Figure 5: Suspended concrete slab on pad footing

2.2 Wall Frames

CFS residential buildings consist of both load bearing and non-load bearing wall panels. The wall panels were fabricated using lipped C sections or C sections (5) as shown in Figure 6. Inner and outer side of the walls are then covered with fiber board such as oriented strand board (OSB) where an insulative layer was placed between the CFS studs using either rock wool, glass wool or any other appropriate insulative material. In some instances, expanded polystyrene (EPS) boards are placed in the middle of the wall to provide insulation. This formulates the basic wall. In addition to the basic wall, inner surfaces are furnished with either medium or high-density boards while external surfaces are designed to withstand humidity, rain and other climatic conditions. The codes recommend the spacing between CFS studs in load bearing walls not to exceed 800 mm.

2.3 Floors

To achieve better insulation and faster construction, similar to timber structures, CFS residential buildings use CFS beams or CFS trusses/joists. Beams or trusses act as a load carrying member and support the timber deck floor as shown in Figure 7. There is an option to have a ceiling underneath the CFS beam or trusses and the insulation is placed between the ceiling and the timber deck. A similar arrangement is used for roof structures and on top of the timber deck, appropriate roofing material.

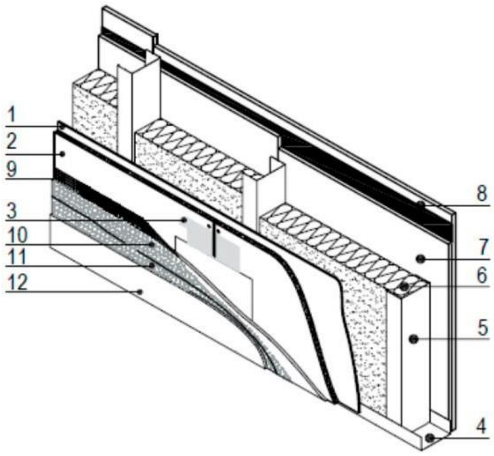

Figure 6: Typical section of a load bearing CFS wall [Reproduced from (Di Lorenzo & De Martino, 2019)]

(a) Truss as a joist (b) C purlin as a joist

Figure 7: Typical Floor in a cold formed steel residential building [Figure 7(a) reproduced from (FRAMECAD, 2022)]

Entire steel used in a CFS load bearing residential building consists steel in an enclosed volume except if any exterior decks constructed using unprotected steel. Designers often make necessary arrangements not to expose the structural steel to external environment. Use of steel in an enclosed volume is referred as "warm frame" as they are less likely to face a drastic environmental changes (Lawson et al., 2010). In order to assess the durability of cold formed steel used in residential construction, data were obtained from the research report RP06-1 published by American Iron and Steel Institute (NAHB Research Center, Inc, 2006), a study by Lawson et al. (2010) in several locations in the United Kingdom, a study by Yoo et al. in Korea (Yoo et al., 2022) and an investigation carried out by LaBoube (2006).

3 CASE STUDIES OF DURABILITY MEASUREMENTS

3.1 Case 1 - Galvanized Steel Framing for Residential Homes (NAHB Research Center, Inc, 2006)

Four test sites were selected by NAHB Research Center to study the corrosion performance of cold formed steels with different types of coatings. The location, environment of the site, type of the foundation ad exterior finish details is given in Table 2 (Site No 1 – 4).

3.2 Case 2: Environmental and Performance of light steel framing building (Baxter, 1990)

One of the earliest light steel frame buildings constructed in 1982 was investigated and reported by Baxter (1990). This Ullenwood building was monitored for five years using galvanized and mild steel test specimen kept inside the wall and loft space. The structure was exposed to oceanic climate with warm summer and cool winter. Baxter (1990) reported the loss in galvanized steel was 0.2g/m^2 peryear where mild steel was observed having a mass loss of 1.26 – 1.62 g/m^2. The data is shown in Table2 (Site No 5).

3.3 Case 3: Student Accommodation Building at Oxford Brookes University (Way et al., 2009)

A demonstration project constructed in 1996 at Oxford Brookes University was investigated for corrosion performance and reported by Way et al. (2009). The site is located in the city of Oxford about 1 km from a river. The study indicated that the depletion of the coating layer was minimal after 5 years when the loss of the coating material was observed between 5- and 10-year period. The study also indicated that the loss of coating mass was significantly higher when they were directly exposed to environmental conditions. The detail of the site is given in Table 2 (Site No. 6).

Table 2: Experimental data obtained from literature and details

Site No.	Location (Distance from water)	Environment	Foundation	Exterior Finish
01	Miami, Florida (Several kilometers)	Humid	Slab on grade	Stucco (similar to cement plaster)
02	Leonardtown, Maryland (25 m from river)	Humid temperate/semi-marine	Crawlspace/Suspended floor	Vinyl siding
03	Long Beach Island, New Jersey (less than 1 km)	Marine	Piers	Aluminum siding
04	Hamilton, Ontario (inland)	Cold winter and industrial	Basement	Brick veneer
05	Ullenwood, England, United Kingdom	Oceanic. Cold winters and warm summers	Suspended ground floor	Masonry
06	Oxford Brookes University, United Kingdom (1 km from river)	Maritime temperate	Suspended ground floor on steel deck	Brick veneer
07	Lisbon Technical University, Portugal	Hot coastal	Slab on grade	Cladding
08	Oahu Island, Hawaii	Tropical	Suspended ground floor	Timber siding

3.4 Case 4: Lisbon Technical University (Way et al., 2009)

Way et al. (2009) reported a study conducted at Lisbon Technical University in Portugal. The site was exposed to hot coastal environment and the samples monitored were kept outside covered by cladding panel on the wall providing an environment of cold air constantly. The surface protection loss was estimated after 5- and 10- year period. The observation indicated the reduction of coating reduces with time as the loss of coating after 5 year period was 1.61 g/m^2 compared to a loss of 2.22 g/m^2 after 10 years. The detail of the site is given in Table 2 (Site No. 7).

3.5 Case 5: Study on coated fasteners by University of Hawaii (Williams et al., 2006)

The University of Hawaii carried out a study on the corrosion resistant nature of zinc coated fasteners and elements. Field enclosures representing actual residential buildings constructed for different exposure conditions were kept at different locations. The climatic conditions are like tropical and exposure to coastal environment that may mimic the conditions of the coastal Sri Lanka as well. The fabricated enclosures were located within 230 m to 1000 m from the coastal line. In each location total climate data was recorded. Details of the site is given in Table 2 (The detail of the site is given in Table 2 (Site No. 7). Qualitative observations made at this site are given in Table 3 (Site No. 8).

4 RESULT AND CONCLUSION

Quantitatively assessed data from seven sites (Site 1 – 7) and qualitative data from one site (Site 8) are compared in Table 3. It can be noticed that the data covers a wide range of climatic and environmental conditions to which the samples were exposed. Among the sites discussed, Miami, Florida (Site 1) and Oahu Island, Hawaii (Site 8) can be considered closely related to coastal area of Sri Lanka while Ullenwood, England can be considered as a climatic condition that may moderately represent hill country of Sri Lanka.

Table 3: Corrosion data from different sites observed from literature

Site No.	**Location (Distance from water)**	**Sample Material**	**Sample Location**	**Exposure duration (months)**	**Mass Loss (grams)**	**Corrosion rate (µm/year)**	**Estimated Life (Years)**
1	Miami, Florida (Several kilometers)	Galvanized 1 (25 µm)	Attic	99	0.02	0.034	367
		Galvalume (41 µm)	Attic	99	0.02	0.066	310
		Galfan (41 µm)	Attic	99	0.04	0.073	280
2	Leonardtown, Maryland (25 m from river)	Galvanized 2 (25µm)	Attic	93	0.02	0.037	367
		Galvalume (41 µm)	Attic	98	0.02	0.066	310
		Galfan (41 µm)	Attic	98	0.02	0.037	554
3	Long Beach Island, New Jersey (less than 1 km)	Galvanized 1 (25µm)	Wall	87	0.02	0.039	320
		Galvalume (41 µm)	Wall	87	0.02	0.075	273
		Galfan (41 µm)	Wall	87	0.02	0.042	488
4	Hamilton, Ontario (inland)	Galvanized 2 (25µm)	Wall	98	0.02	0.035	357
		Galvalume (41 µm)	Wall	98	0.02	0.066	310
		Galfan (41 µm)	Wall	98	0.02	0.037	554
5	Ullenwood, England, United Kingdom	Galvanized (20 µm)	Wall (Cold cavity)	60	1.2	0.034	294
			Loft (Cold frame)	60	0.59	0.017	588
6	Oxford Brookes Univesrity, United Kingdom	Galvanized (20 µm)	Cold loft space	60	0.57	0.016	625
			Wall - Up	60	0.47	0.013	769
			Wall - low	60	1.25	0.035	286
			Below ground floor	60	2.13	0.060	267
			Cold loft space	124	0.63	0.009	1111
			Wall - Up	124	0.45	0.006	1667
			Wall - low	124	1.31	0.018	556
			Below ground floor	124	2.04	0.029	552
7	Lisbon Technical University, Portugal	Galvanized	Cold Wall Cavity	60	1.61	0.045	222
			Cold Wall Cavity	123	2.22	0.031	323
8	Oahu Island, Hawaii	Galvanized	Wall framing	Tightly sealed volumes demonstrated no corrosion. Vapour barrier observed providing additional protection			
			Wall framing	If there was any leak of airflow in the frame, evidence of corrosion was observed			
			Vented attic	Evidence of corrosion was observed when there was a good exposure to chloride rich wind flow			
			Crawl Space	Evidence of corrosion was observed when there was a good exposure to chloride rich wind flow			

The quantitative data given in Table 3 in general represent the most critical exposure conditions. For example, at site no.5, the critical data was observed inside the wall and loft. Considering most of the critical values, some of the experimental data were obtained from the literature are not presented inorder to make a impactful outcome considering Sri Lankan scenario.

Exposure duration and mass loss were recorded by relevant authors(Baxter, 1990; NAHB Research Center, Inc, 2006; Way et al., 2009; Williams et al., 2006). Corrosion rate was calculated using the method given in ASTM G1-03 (G01 Committee, 2017). Equation (1) given below can be used to determine the corrosion rate in galvanized steel elements.

$$Corrosion\,rate = (KW)/(ATD) \tag{1}$$

Where, K = constant = 8.76 X 10^7 µm/year

W = mass loss in grams

A = area in cm^2

T = time of exposure in hours

D = density in g/cm^3, a value 7.13 g/cm^3 was assumed for zinc, 6.7 g/cm^3 was assumed for Galfan, 3.75 g/cm^3 was assumed for Galvalume.

Corrosion rates shown in Table 3 were calculated using the Equation (1). Site 1 to 4 have used three different types of coating namely galvanized, Galvalume and Galfan. Galvanized coating is applied by dipping the steel inside 99% zinc to achieve the coating. There are two thicknesses that were used. Some samples have used 38µm thick coating while some have used 29µm coating. Durability is proportional to the thickness of the coating(Lawson et al., 2010). Therefore, the thicker the coating, the better the protection. As discussed earlier, Galvalume is a composition developed using 55% Aluminum, 43.5% Zinc and 1.5% silicon. If thickness of the coating is considered, Z275 coating (99% zinc 275g/m^2) and AZ150 (Galvalume 150g/m^2) provide the same thickness of 20µm. The Galfan coating is a composition using 95% Zinc, 5% Aluminium and 0.05% mischmetal (Yoo et al., 2022). It can be observed from the data recorded on similar environmental conditions that galvanized elements demonstrate better resistance to corrosion than Galvalume and Galfan. The data recorded at Hamilton, Ontario show that Galfan shows better resistance than Galvalume in cold and industrial areas. However, conventional galvanized coating indicates a comparable corrosion resistance like Galfan.

4.1 Corrosion observations in wall area

The wall area can fall into two categories. The first category is a well-protected wall like the one shown in Figure 6. The well protected wall area will have a lower level of humidity and dry environment to achieve a higher level of insulative properties. In modern buildings, a U value in the range of 0.15 – 0.25 W/m^2/^{o}C is expected to meet the stringent energy guidelines (Lawson et al., 2010). Therefore, the walls in general will have a well-sealed environment that reduces humidity and wetness.

Galvanized wall elements record a corrosion rate of 0.028 – 0.035µm/year under different climatic conditions. The rate of corrosion further reduces when the data is obtained for a longer duration as observed from Table 3. It can be also observed that there is no significant difference between cold wall environment and warm frame environment. Lawson et al (2010) proposed an equation that can be used to determine the design life of a cold formed steel element based on the exposure conditions. It was argued that for elements that are in concealed environments to be assumed to have reached the service life once 50% of zinc coating is lost. In cases where the cold formed steel elements were visible and easy to inspect, the service life can be determined based on 80% loss of the zinc coating. The following equations (Equation 2 and Equation 3) were proposed by Lawson et al (2010) to estimate the design life of cold formed steel elements. Equation 2 can be used for concealed steel elements and equation 3 can be used for exposed and visible elements.

$$Design\ life\ of\ concealed\ elements = 0.25\ x\ \left(\frac{Total\ weight\ of\ zinc\ coating}{rate\ of\ the\ zinc\ loss\ per\ year}\right) \tag{2}$$

$$Design\ life\ of\ visible\ elements = 0.40\ x\ (\frac{Total\ weight\ of\ zinc\ coating}{rate\ of\ the\ zinc\ loss\ per\ year}) \quad (3)$$

Design life calculated using equations (2) for wall, attic and loft spaces and the same calculated for exposed members such as below ground floor area using equation (3) by the authors are listed in Table 3.

4.2 Corrosion observations in attic, loft, and exposed elements

Like walls, attic and loft areas under an enclosed environment, spaces show reduced corrosion rates. However, exposed steel such as CFS below ground floor have seen a significant increase in corrosion rate as shown in Figure 8. A lower rate for upper part of a wall (labelled 1) is noticed while during the same period a 6 times higher rate was observed for exposed steel below ground floor (labelled 3). A similar observation was noticed at different durations as shown in Figure 8.

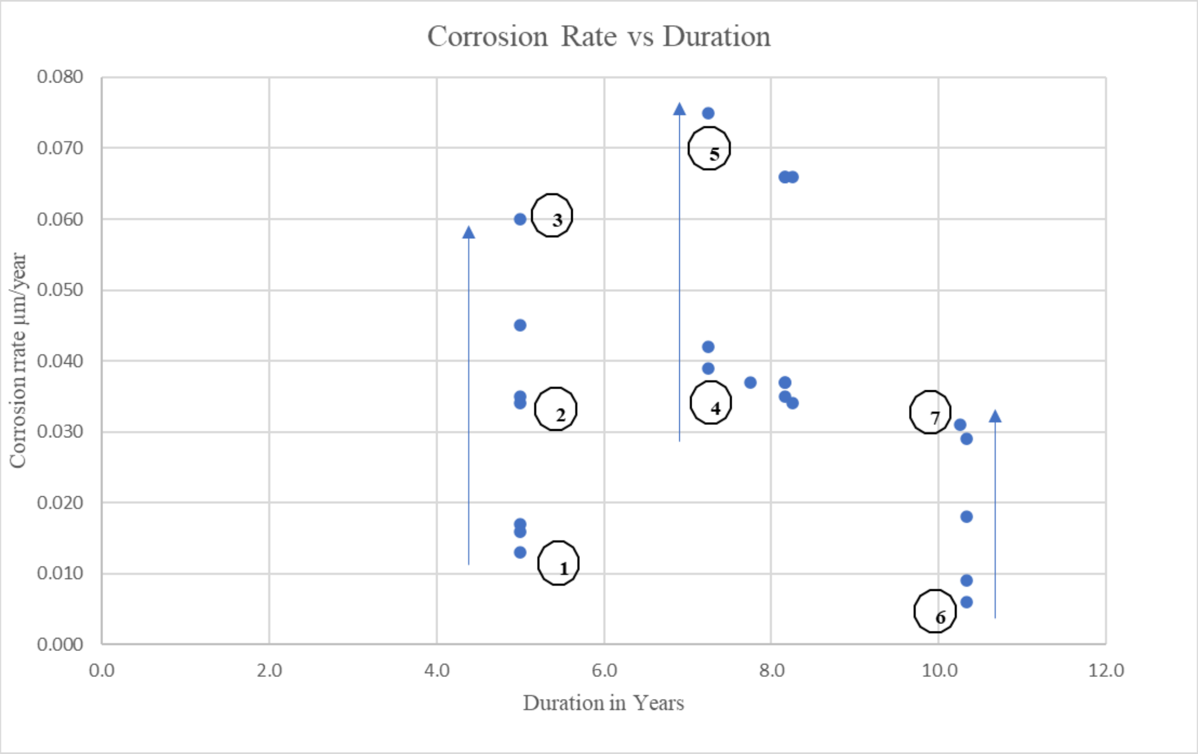

Figure 8: Corrosion rate vs Duration (1- Upper part of a wall, 2- Lower part of a wall, 3 – below ground floor, 4 – Galvanized wall, 5- Galvalume wall, 6 – Upper part of a wall, 7 – below ground floor)

4.3 Conclusion

Comparison of the data obtained from literature can help us to draw the following conclusions at large.

- If the building envelope is properly maintained, Galvanized, Galvalume and Galfan coatings can provide a minimum of 200 years of design life. Residential buildings are designed and constructed for a service life of 50 years. Therefore, like other construction materials, Cold Formed Steel can be considered as an efficient and reusable material for construction.
- Although the exposed elements such as steel below ground floor or under decking show acceptable corrosion rate, frequent observation and maintenance can increase the durability of the material through timely intervention.

- The data presented in Table 3 covers different geographical and climatic conditions. Corrosion rate found in a humid (Site 1), marine (Site 3), cold winter (Site 4) and hot coastal (Site 7) climate conditions show a similar rate of corrosion at different periods considered. This indicate that independent of the climatic or exposure conditions, the details adopted for the design ensuring the protection of the steel helps to achieve better durability.
- Similar to any other materials, appropriate design envelope that protect the material sufficiently can help to utilize the benefits of CFS in residential construction.
- The following procedures can help to enhance the durability of the galvanized steel.
    - Maintaining the exterior of the building to ensure degradation in exterior leads to deterioration of the internal material (As observed in Site 8, a leak on exterior wall can accelerate corrosion of the internal steel).
    - Prevent extended contact with moisture from occurring through water infiltration. Appropriate design methods can be adopted to prevent vapor, moisture and rainwater.
    - Ensure galvanized steel does not come into direct contact with harsh or wet materials, such as at the foundation or in exterior walls. Design procedures adopted to achieve enhanced thermal insulation in general prevent steel from such direct contacts.
    - Prevent water trapped inside the building envelop.

By adopting appropriate design methods and detailing, cold formed steel can make an attractive alternative to other construction materials within Sri Lankan context owing to the facts observed analyzing the durability data obtained from literature. A detailed investigation on durability of cold formed steel in different climatic conditions of Sri Lanka can complement the research.

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