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MAXIMUM HORIZONTAL LONGITUDINAL FORCE DUE TO CRANE LOADING USING A COUPLED APPROACH

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ABSTRACT

Horizontal longitudinal forces arise when a crane collides with the end stops of the crane supporting structure. Previous research work found that several parameters have a significant effect on the horizontal longitudinal force response during the collision sequence. The maximum horizontal longitudinal force from this research work was obtained through extensive Finite Element Analysis simulations by considering the parameters as uncoupled; that is, the phase of each parameter was adjusted individually while the other parameters' phases remained unchanged. The approach could be questioned as the parameter's phases do not act individually and thus cannot be studied in isolation as the combined parameters effect could either increase or decrease the horizontal longitudinal force. These concerns led to this investigation to determine whether the maximum horizontal force obtained from previous investigations yield realistic maximum horizontal longitudinal forces.An investigation was conducted using a coupled approach by cumulatively adding the parameters with their respective phases to obtain the maximum horizontal longitudinal force. This was achieved by considering the parameters with both their maximum phases and their adjusted phases. The results showed that the impact force response is non-linear when the maximum and adjusted phases are used to determine the horizontal longitudinal force. Furthermore, the investigation showed that the South African Code of Practice, SANS 10160-6, as well as the Eurocode, EN 1991-3, is conservative in its estimate of the horizontal longitudinal force when the crane collides with the end stops of the crane supporting structure. As a result, the end stops would prevent the crane from running off the crane rails during a collision if the masses of the crane and the full payload are used to determine the horizontal longitudinal force.

KEYWORDS

Horizontal longitudinal forces, Coupling parameters, Overhead travelling crane, Finite Element Analysis

1. INTRODUCTION

Cranes are mechanical devices which are used to hoist and move equipment to a specific location within industrial environments. The mass of the hoisted equipment ranges from insignificant to several hundred tons, depending on the operating requirements of the crane. Cranes are therefore designed for specific industrial applications. As a result, there are many different types of crane which can be broadly classified into: mobile cranes, fixed cranes and overhead cranes. Within these classifications there are numerous subcategories of cranes.

This paper focuses on overhead cranes, with specific emphasis on determining the horizontal longitudinal forces that the crane exerts on its supporting structure. A brief overview of overhead cranes is provided. Overhead cranes can be either manually controlled for insignificant loads or electrically operated for significant loads. Of these, electric overhead travelling cranes are the most popular for use in industrial buildings to move heavy or cumbersome equipment. These types of crane are manufactured as either a single or double bridge girder which is either top running or underslung. The choice of crane is usually governed by the horizontal lateral span, the hoist load and the vertical constraints of the building. These cranes are renowned for their durability, high performance, high efficiency rate and their reasonable manufacturing cost. Figure 1 shows a 5 ton single bridge girder top-running electric overhead travelling crane (yellow structure) with its supporting structure (brown structure). Various components of the crane and its supporting structure are also identified in Figure 1. The components of the crane supporting structure are designed by structural engineering professionals to the requirements specified in the codes of practice, while the components of the crane are designed by the crane manufacturer.

Figure 1: A 5 ton single-top running electrical overhead travelling crane

The crane supporting structure must therefore be designed to resist the vertical and horizontal loading caused by the electric overhead travelling crane (EOHTC) and the payload for the worst possible scenario, i.e. whether the crane is stationary or moving. Since this paper only focuses on the horizontal longitudinal forces, the codified requirements for the vertical load and the horizontal transverse load is be omitted from this paper.

2. LITERATURE REVIEW

2.1 Codified Approach

A thorough review of existing literature revealed that several codes of practice addresses the phenomena of longitudinal horizontal forces (end buffer impact forces) which the crane imposes on its supporting structure; [1], [2], [3] and [4]. Various codes use different design philosophies to determine the longitudinal horizontal forces, which leads to a significant variation in results, [5,6,7]. To complicate the situation, no literature was obtained providing background to the methodology and expressions presented in the codes. This leaves the design engineer unsure whether a specific code yields realistic results.

In South Africa, the code of practice which governs the actions of cranes and machinery on buildings is SANS 10160 part 6, which is almost a verbatim repetition of the European Committee for Standardisation 1991,EN 1991-3:2003. The differences between these codes do not affect the magnitude of the horizontal longitudinal force. The approach used by SANS 10160 part 6 will be used to determine the codified horizontal longitudinal force. SANS 10160 – 6 specifies that the horizontal longitudinal force can be obtained as a result of either the crane transversing on the crane rails or the collision of the crane with the end stops of the crane supporting structure. Clause 4.7.2 of SANS 10160 – 6 specifies that the horizontal longitudinal force due to the acceleration/deceleration of the crane be determined using equation 1.

$$H = \emptyset_5 \times K \times \frac{1}{n_r} \tag{1}$$

where;

"H" is the horizontal longitudinal force exerted on each rail.

"ϕ_5" is the dynamic factor which varies from 1 to 3. A value of 1 is used for cranes with centrifugal forces, while a value of 3 should be used for cranes with drives having considerable backlash.

"K" is the drive force of the individual motor. This can be obtained from the manufacturer or determined using the product of the friction and vertical wheel loads.

"n_r" is a factor to account for the number of rails.

Using equation 1 and the properties used by Haas [5]; i.e. a crane mass of 2 083 kg and a crab mass of 150 kg, a horizontal longitudinal force of 2.19 kN was obtained for $\phi_5 = 1$ while a force of 6.57 kN was obtained for $\phi_5 = 3$. Thus a maximum estimated codified horizontal longitudinal force of 6.57 kN was obtained due to the acceleration/deceleration of the crane.

In addition, Clause 4.12.2 of SANS 10160 - 6 also specifies that the collision between the crane and the end stops be considered as an accidental load case. The horizontal longitudinal force as a result of this collision can be determined using equation 2.

$$H = \emptyset_7 \times v_1 \times \sqrt{m_c \times S_B} \tag{2}$$

where;

"H" is the horizontal longitudinal force exerted on each end stop

"ϕ_7" is the dynamic factor

"v_1" is the impact velocity which can be reduced by 30% if the crane is fitted with automatic speed-retarding mechanisms close to the ends of the crane rails.

"m_c" is the combined mass of the crane and the payload

"S_B" is the spring constant of the elastomeric cellular plastic buffers

Using the additional properties of a payload mass of 5 128 kg, an impact velocity of 0.55 m/s which was reduced by 30% and DPZ 100 elastomeric cellular plastic buffers manufactured from DEMAG, Haas [5] obtained a maximum codified horizontal longitudinal force of 23.9 kN. The codified estimation is based on an uncoupled approach to reduce the complexity of the problem since the code does not consider all the parameters and its phases during the collision.

The horizontal longitudinal force due to the acceleration/deceleration of the crane is omitted from any further investigation since it is significantly smaller (363%) than that obtained from the collision condition.

2.2 Previous Published Work

To determine the accuracy of the codified horizontal longitudinal force, Haas [5] found several parameters which have an effect on the horizontal longitudinal force history. The identified parameters are:

- The vertical angle of inclination of the cable and the payload during longitudinal travel.
- The crab and payload eccentricity on the crane bridge.
- The impact velocity of the crane.
- The damping characteristics of the elastomeric cellular plastic buffers.
- The longitudinal motors fully engaged during the collision cycle.
- The horizontal misalignment of the end stops.
- The flexibility of the supporting structure.

The last two parameters can be ignored from any investigation if proper and regular maintenance is performed on the crane and its supporting structure. For this reason the last two parameters were ignored in this investigation. SANS 10160 – 6 as with other codes ignores the possibility that the longitudinal motors can be fully engaged during the collision cycle. Haas [6] included this effect in their investigations.

In a subsequent paper, Haas [6] determined a realistic range of variation of each parameter shown in Table 1. The parameters with its range of variation were used to conduct a sensitivity analysis using a Finite Element (FE) model developed in ABAQUS.

Table 1: Parameters with its corresponding phase angle

Parameter	**Payload 0.15m above ground level**		**Payload 2.20m above ground level**		**Realistic phase**
	1st impact	**2nd impact**	**1st impact**	**2nd impact**	
Lag angle	$+2.5^0$	-2.5^0	$+2.5^0$	-2.5^0	1.25^0
Crab and payload eccentricity	0.75 m LHS	0.75 m LHS	0.75 m LHS	0.75 m LHS	2.14 m from LHS edge
Crane speed	+0.05 m/s	+0.05 m/s	+0.05 m/s	+0.05 m/s	+0.55 m/s
Buffer damping characteristics	No damping	No damping	No damping	No damping	Damping reduced by 25%

Figure 2 shows the horizontal longitudinal force response with the phase angle of the individual parameters selected in such a manner to obtain the largest first impact force when the cable is 2.45 m long. This resulted in the payload being 0.15 m above ground level. It is important to note that these responses were achieved by individually varying each parameter at its maximum anticipated phase while all other parameter phases were kept constant at its base state.

Figure 3 shows the horizontal longitudinal force response with the phase angle of each parameter selected in such a manner as to obtain the smallest first impact force when the payload is hoisted 0.15 m above ground level. This was achieved by individually varying each parameter at its minimum phase while the phase of all other parameters was kept constant.

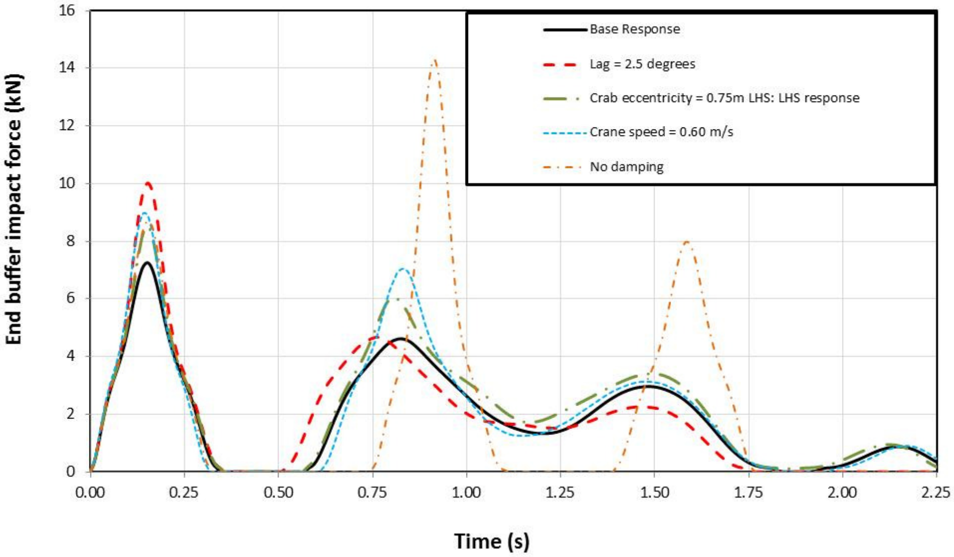

Figure 2: Horizontal longitudinal force response resulting in the largest first peak when the payload is hoisted 0.15 m above ground level; i.e. a cable length of 2.45 m

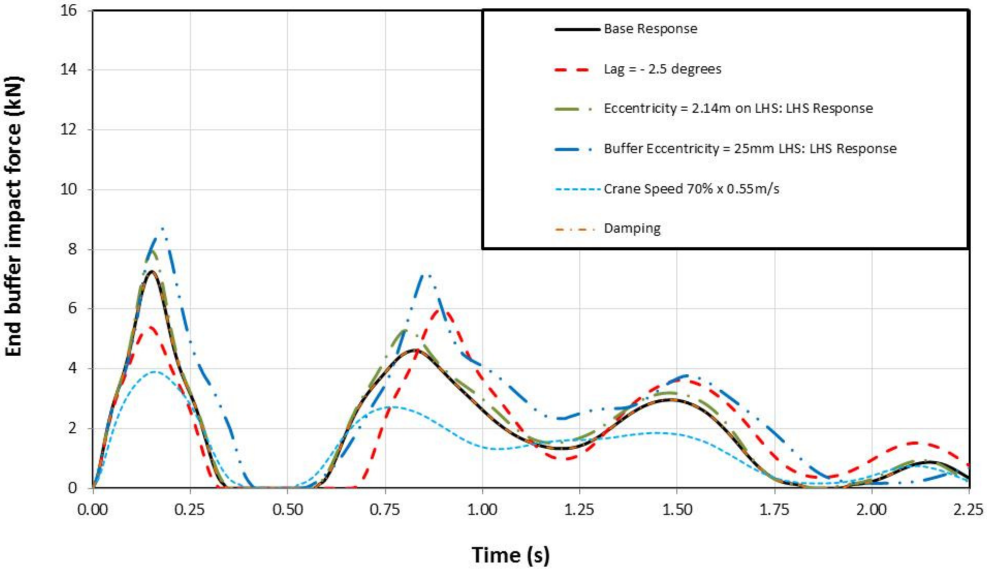

Figure 3: Horizontal longitudinal force response resulting in the smallest first peak when the payload is hoisted 0.15 m above ground level; i.e. a cable length of 2.45 m

From Figure 2 it is observed that the largest first and second impact forces are 10.03 kN and 14.33 kN, respectively, and from Figure 3 that the largest first and second impact forces are 8.69 kN and 7.21 kN, respectively. Figures 2 and 3 highlight the significant variation in the horizontal longitudinal force response by simply adjusting the phase of a single parameter while the remaining parameters are kept constant. Another important observation is that the occurrence of the first peak is insignificantly affected whereas the second peak is significantly affected by the adjustment of the parameters phase.

Haas [6] conducted FE simulations when the payload is hoisted 2.20 m above ground level, which resulted in the payload being 0.35 m below the crane bridge. The FE simulations produced similar trends with respect to the horizontal longitudinal force and the position of these peaks compared when the payload is hoisted 0.15 m above ground level.

The FE simulations revealed that the largest horizontal longitudinal force can occur at either the first or second peak when the payload is hoisted 0.15 m or 2.20 m above ground level. The maximum horizontal longitudinal force could therefore not be obtained by simply selecting the largest impact force since only a single parameter was varied during each numerical simulation while all other parameters remained constant, which is an unrealistic approach compared with reality. This approach resulted in the parameters being uncoupled during the FE simulations. To ensure a coupled approach, Lagrange multipliers, a constraint optimisation technique was used to determine the maximum horizontal longitudinal force for a given level of reliability. A maximum horizontal longitudinal force of 14.54 kN was obtained for a reliability index, β, of 3. A reliability index of 3 was chosen for this investigation as most countries use this value in their code calibration. This resulted in the codified estimate being 165% greater than the horizontal longitudinal force obtained using Lagrange multipliers.

A shortcoming of the work by Haas [5, 6] is that the maximum horizontal longitudinal force was not determined by coupling various parameters to conduct experimental tests and FE simulations. Coupling in this context refers to the parameter's phases acting together. They concede that it was difficult to group parameters during experimental testing since it was impossible to accurately control all significant parameters; e.g. the lag angle of the payload as it oscillates during the acceleration and during constant-velocity travel. However, all the parameters could be controlled with extreme accuracy in the FE simulations. Therefore, the purpose of the present investigation was to determine the maximum horizontal longitudinal force by coupling parameters with their phases; i.e. to consecutively add the parameters during the FE simulations. The results of these FE simulations would be compared with the initial estimate by Haas [5, 6] as well as with the codified estimate.

Besides the work of Haas [5, 6, 7, 8], no other peer-reviewed publications were found which directly or indirectly address the horizontal longitudinal force exerted by the crane on the crane supporting structure when elastomeric cellular plastic end buffers are used.

3. EXPERIMENTAL CONFIGURATION AND NUMERICAL MODEL

Since the experimental configuration and the modelling thereof are not essential to this paper, the reader is referred to Haas [5] for a brief description or to Haas [7] for a detailed description of the experimental configuration, and to Haas [8] for a detailed description of the FE model. The above papers present all necessary detail of the experimental model and how a computationally efficient FE model was developed.

4. METHODS

This investigation was performed using a numerical approach since it is very difficult to accurately control the parameters during experimental tests. To achieve this objective, the same FE model developed by Haas [7] was used in this investigation. Minor adjustments were required to the existing FE model to allow the parameters to be consecutively added to obtain a coupled approach. This was achieved by:

i. Consecutively adding the individual parameters with their maximum phase identified in Table 1 when the payload is hoisted 0.15 m and 2.20 m above ground level to produce a coupled approach. This resulted in condition 1 for the 0.15 m case and condition 3 for the 2.20 m case. The parameters with its phase were consecutively added in the following order namely; cable lag angle of 2.5^0, horizontal lateral crab and payload eccentricity of 0.75 m from the end of the crane bridge, crane speed of 0.6 m/s and the buffer damping omitted.

ii. Consecutively adding the individual parameters with a realistic phase identified in Table 1 when the payload is hoisted 0.15 m and 2.20 m above ground level to produce a coupled approach. This resulted in condition 2 for the 0.15 m case and condition 4 for the 2.20 m case. The parameters with its phase were consecutively added in the following order namely; cable lag angle of 1.25^0, horizontal lateral crab and payload eccentricity of 2.14 m from the end of the crane bridge, crane speed of 0.55 m/s and with the buffer damping reduced by 25%.

iii. The FE analysis for i and ii were conducted with the machine motors fully engaged during the collision sequence. This effect is ignored by all the codes which were reviewed. This parameter however has a significant influence on the horizontal longitudinal force response.

iv. Comparing the results from (i) and (ii) with those obtained from the codified response and from Haas [6].

5. RESULTS AND DISCUSSION

Table 2 shows the magnitudes of the horizontal longitudinal force as each parameter is consecutively added for each condition, i.e. 1 and 3, with the parameters in their maximum phase.

Table 2: Horizontal longitudinal force with parameters at ***maximum***phase

Condition number anddescription of the parameters	**Impact location, i.e. 1s or 2^{nd} impact, with the vertical height above ground level**	**Base force** (No lag, no crab and payload eccentricity, speed = 0.55 m/s, 100% damping) **(kN)**	**Lag angle included** (2.50^o) **(kN)**	**Crab and payload eccentricity included** (0.75m from the LHS of the crane bridge) **(kN)**	**Crane speed included** (Crane speed 0.6 m/s) **(kN)**	**Buffer damping character-istics** (No damping) **(kN)**
1 Maximum parameter magnitude	1st peak 0.15 m	7.26	10.03	12.77	15.79	17.40
	2nd peak 0.15 m	4.61	4.67	7.42	11.47	19.13
3 Maximum parameter magnitude	1st peak 2.20 m	7.48	9.92	13.30	15.96	17.34
	2nd peak 2.20 m	8.05	8.52	11.09	14.22	**22.21**

Table 3 shows the magnitudes of the horizontal longitudinal force as each parameter is consecutively added for each condition, i.e. 2 and 4, with the parameters in their adjusted (realistic) phase.

Table 3: Horizontal longitudinal force with parameters at ***adjusted*** phase

Condition number anddescription of the parameters	**Impact location, i.e. 1s or 2nd impact, with the vertical height above ground level**	**Base force** (No lag, no crab and payload eccentricity, speed = 0.55 m/s, 100% damping) **(kN)**	**Lag angle included** (1.25°) **(kN)**	**Crab and payload eccentricity included** (2.14 m from the LHS of the crane bridge) **(kN)**	**Crane speed included** (Crane speed increased by ≅ 5% to 0.575 m/s) **(kN)**	**Buffer damping character-istics** (Damping reduced by 25%) **(kN)**
2 Adjusted parameter magnitude	First peak 0.15 m	7.26	8.79	9.44	10.82	11.25
	Second peak 0.15 m	4.61	4.44	5.85	7.01	8.95
4 Adjusted parameter magnitude	First peak 2.20 m	7.48	8.64	10.08	11.07	**11.33**
	Second peak 2.20 m	8.05	8.31	8.93	9.86	11.17

From Tables 2 and 3 it is observed that the first and second horizontal longitudinal force peaks gradually increases as the parameters are consecutively added for all conditions. This response is anticipated since each parameter is expected to increase the magnitude of the horizontal longitudinal force. It is also observed that the largest impact force of 22.21 kN occurs when the parameters' maximum phases are used. This force is 276% greater than the corresponding base state of 8.05 kN. This force although not impossible has an unlikely probability of occurring since it is not expected that the parameters would all act with its maximum phase during the collision cycle. However, when the parameters' phases are adjusted to realistic magnitudes during the collision cycle a maximum force of 11.33 kN was determined as obtained from Table 3. This force yields an increase of 51% above its base state.

The results in graphical format for conditions 1 and 2 are presented in Figure 4, while conditions 3 and 4 are presented in Figure 5, together with the codified result and the uncoupled maximum horizontal longitudinal force obtained by Haas [6].

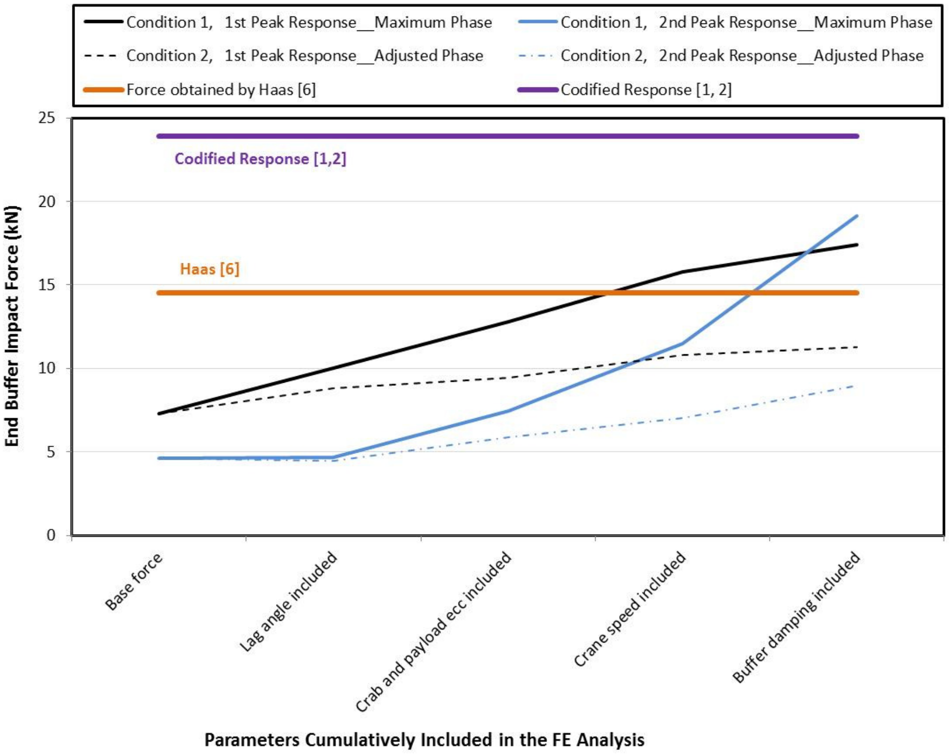

Figure 4: Cumulative longitudinal force response with the payload 0.15 m above ground level

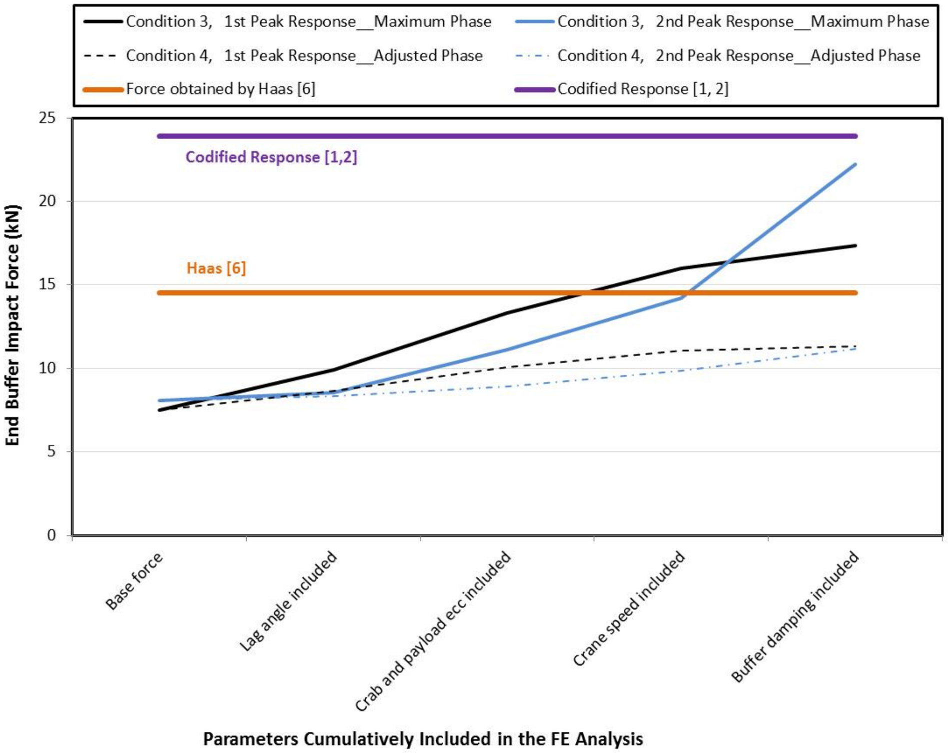

Figure 5: Cumulative longitudinal force response with the payload 2.20 m above ground level

It is noted that conditions 1 and 3 will yield unrealistically high horizontal longitudinal forces as it will rarely happen that all the parameters will act with their maximum phases at the moment of impact. A more realistic horizontal longitudinal force would occur when the maximum phase is reduced to a realistic phase as shown in the last column of Table 1.

6. CONCLUSIONS

A FE investigation was conducted to determine whether the codified results obtained from EN 1991-3:2003 and SANS 10160 – 6 as well as Haas's[5, 6, 7, 8] previous work produces realistic horizontal longitudinal forces based on an uncoupled parameter approach. This was achieved by consecutively adding parameters leading to a coupled approach to obtain an upper bond (maximum parameter phase) and realistic (realistic parameter phase) horizontal longitudinal force.

A horizontal longitudinal force of 23.9 kN was obtained for the codified approach while a force of14.33 kN was obtained by Haas [6]. The magnitude for the upper bond and the realistic horizontal longitudinal forces from the coupled FE simulations were obtained as 22.21 kN and 11.33 kN, respectively. Simply based on this, an argument could be made that the code is slightly conservative by 7%, compared with the coupled parameter approach's upper bond. It should however be noted that the upper bond force was obtained with all the parameters at its maximum phase during the collision cycle. The probability of all the parameters acting in unison at its maximum phase is an extremely unlikely event. The code significantly overestimates the horizontal longitudinal force by 210% compared with the realistic coupled parameter approach. The realistic coupled parameter approach underestimates the uncoupled parameter approachby 21%.

Since the manufactured cost of the end stops is insignificant compared with the overall cost of the crane and the crane supporting structure, the author believes that the requirements of the code remain unchanged, even though the code yields extremely conservative results.

This investigation shows that SANS 10160 Part 6 and EN 1991-3: 2003 conservatively estimate the horizontal longitudinal force when the crane collides with the end stops of the crane supporting structure. Therefore, the end stops would definitely prevent the crane from running off the crane rails during a collision if the masses of the crane and the full payload are used to determine the horizontal longitudinal force.

7. REFERENCES

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