OVERLOADING OF HIGHWAY BRIDGES - INITIATION OF DECK DAMAGE

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Various surveys have indicated that highway bridges are subjected to vehicular load levels and combinations far in excess of those for which they were designed. The prediction of the effects of the overloading as well as the overload permit operations do not reflect the sophistication scientific or technical fields have attained. The paper presents the findings of a parametric investigation employing Program BOVA (Bridge OVerload Analysis), that encompasses 45 case studies. Five different commonly encountered overload vehicles and nine different bridge configurations are considered. The bridge superstructures are simple span beam-slab bridges with prestressed concrete I-beams and reinforced concrete deck, and having no skew. The results of the findings are presented in tabular form for the bridges and the overload vehicles. For given bridges and vehicles the gross vehicular weights, axle weights and "equivalent area loads" are defined that will induce cracking in the concrete that will reach the reinforcing bars. It has been found that if a small amount of damage to the bridge deck is permitted, the load levels which the superstructure can carry are usually in excess of the commonly reported permissible overload weights. Recommendations have been made for the use of the tabulated results in overload permit operations. It has been suggested that the findings can be applied to overload permit operations in the absence of reliable methods of predicting the overload response of bridges. It is also indicated that the suggested guidelines are useful for infrequent traverses of vehicles until the completion of research programs that will delineate the permissible and impermissible overloadings that will be based on limited damage criteria.

Various surveys have indicated that a substantial percentage of existing bridges is in some state of structural distress. Furthermore, it has been found that a noticeable number of overload vehicles traverse these bridges, with or without overload permits (1,2). Permit operations, as well as the assessment of the strength of bridge superstructures when subjected to a given overload vehicle, still are not fully based on rational methods (2,5). To the extent that the vehicular configuration differs from the standard design truck (5), the use of distribution factors and similar design aids will lead to increasingly incorrect results. Any analysis scheme based on linear elastic behavior will also lead to conservative results since this approach will ignore the ever present material nonlinearities and the redistribution of stresses in the superstructure (2). Similarly, the ultimate strength approach will not yield much useful information. There may be a substantial difference between the collapse load level and the load level which will induce limited damage to the structure.

Program BOVA

To predict the overload response of simple span beam-slab bridge superstructures with reinforced or prestressed concrete I-beams and reinforced concrete deck, a research program was undertaken. A computer based simulation technique using a finite element method was developed which predicts the behavior of a given superstructure for a given vehicle, including the initiation and spread of damage, if any, damage characteristics, and collapse (2,3). The research has resulted in Program BOVA (Bridge OVerload Analysis) which simulates the full range elastic and inelastic behavior of the superstructure (3). A comparison of the results obtained in field testing of bridges and prediction of their behavior via Program BOVA has indicated that the maximum discrepancy between the results is 5%. This is far more accurate than the current "methods" employed in permit and rating operations.

Research has indicated that superstructures have enough reserve strength to carry substantially heavy overload vehicles, if a limited amount of damage is permitted to the superstructure (1,2,3). The damage to the superstructure has invariably started as flexural cracking of the deck slab. If the "permissible damage," e.g. crack depth, is related to the "serviceability limits," which may be imposed by transportation authorities, and if a minimal amount of cracking is permitted to take place, then it will be possible to determine vehicular load levels that can be realistically permitted to traverse the bridges infrequently. The basic premise in permitting a minimal amount of cracking is the fact that the deck slab is already cracking due to such factors as construction, freeze-thaw, and overloading. Thus, to allow limited cracking will not lead to an uncontrolled increase in vehicular weights; on the contrary, it will impose maximum limits which are based on scientific findings.

Parametric Study

Research has indicated that the identification of the common factors that can be employed in conjunction with the assessment of the strength of superstructures and overload permit operations requires a major parametric study. After such a study, it will be possible to simplify the permit operations for a majority of the cases encountered into a "table look-up," rather than executing Program BOVA for each case. A limited parametric investigation to fulfill this purpose has been carried out. Extensive details of the findings of this study in the form of Overload Directories have been reported elsewhere (1). These Overload Directories can be used for permit operations with great ease, even by unskilled personnel (1). Due to space limitations, this paper will present only the information dealing with the initiation of the deck slab cracking. Within the framework of this paper the loads that cause "deck cracking" are defined as the loads which will induce cracks through the full depth of the concrete cover of the reinforcing bars at the top and/or bottom of the slab.

The parametric investigation included nine bridges with various span lengths designed in accordance with the recent design guidelines (1,4). Beam spacing was taken as 2.29 m (7'-6") for all bridges. The pertinent dimensions of the bridges can be seen in Figures 1-3. Five different overload vehicle configurations have been considered; they approximate a vast majority of the vehicles encountered in the traffic stream in and between metropolitan areas. Figures 4 through 8 show the plan and elevation of these vehicles, and axle weights. The parametric study, excluding the additional pilot cases, contained 45 case studies (1).

Deck Damage

For given bridges and vehicular configurations, as indicated in Figures 1-8, the gross vehicular weights that result in the cracking of the deck are seen in Table 1. It should be noted that gross weights are not the same as those indicated in the figures. For example, Vehicle 2 has a gross weight of 427 kN (96 kips). If this vehicle is on Bridge 1 or 4 the tabulated weights are 476 kN (107 kips) and 325 kN (73 kips) respectively. Therefore, it can be concluded that if this vehicle traverses the bridges, Bridge No. 1 will not sustain significant damage, whereas Bridge No. 4 will have excessive deck cracking. Since the threshold limit is 325 kN (73 kips), it is expected that substantial damage to the deck may take place. In order to cause "deck cracking" in Bridge No. 1 the axle weight of the vehicle can be increased up to 159 kN (36 kips), which is in excess of the original vehicle, which has an axle weight of 142 kN (32 kips).

Inspection of Table 1 indicates that it is hard to draw any conclusions by studying the gross vehicular weight, which varies from 325 kN (73 kips) to 587 kN (132 kips). Table 1 also contains the axle weights for the case studies presented herein. There still exists a wide variation among the axle weights that induce deck cracking, with the spread from 88 kN (20 kips) to 185 kN (42 kips). It can be concluded that overload permit operations and the assessment of the strength of the superstructures should not be solely related to the axle weights. In Table 2 average axle loads for different bridge span lengths have been presented. Even though there is a large standard deviation, the average axle weights are in the vicinity of 125 kN (28 kips). Therefore, for the lack of any other information, the maximum axle weights should not exceed this value, if only a limited amount of cracking is to be permitted.

Another guideline in the determination of the vehicular loading is the use of equivalent area load. The equivalent area is defined as that enveloping the extremities of tire prints. It should, however, be noted that the accuracy of this approach depends on the use of multiple axles and multiple wheels per axle. The equivalent pressure is obtained by dividing the gross vehicular weight by the equivalent area. In Table 1 the pressure varies from 30 kPa (1.44 ksf) to 70 kPa (3.35 ksf). Again, inspection of Table 2 indicates that, as it is for the average axle weights, the average equivalent pressure is relatively constant with a small standard error in the mean, but with a large standard deviation. Consequently, due to the absence of more reliable guidelines, it is recommended that for limited cracking in the deck slab the equivalent area load should not exceed 47 kPa (2.25 ksf). The above guidelines are rather crude benchmarks. A more accurate prediction of the vehicular weights, permitting limited deck cracking, can be obtained on a case by case basis by using Table 1. One of the bridges, presented herein, that is similar to the actual bridge, and one of the vehicles, presented herein, that is similar to the actual vehicle can be used to enter Table 1. Depending upon the listed weight versus actual weight, a decision can be reached for the issuance of the overload permit. It is possible to interpolate between different bridges and vehicles included in the paper; however, this leads to a gradual loss of accuracy of the prediction of the threshold value. Detailed application of Overload Directories to permit operations is presented in Reference 1. For permit and rating operations the use of this reference is strongly recommended.

Additional research is currently underway ("Implementation of Program BOVA"). At the completion of this research more information in the form of Overload Directories will be available, which will also include information on the overloading of deteriorated bridge decks.

Conclusions

Rating and permit operations for highway bridges (1) should not be based on "reverse design" process and (2) preferably should not be based on an elastic analysis. These will lead to either erroneous or conservative results. In the overloading of bridges, the damage initiates through the flexural cracking of the deck slab. If a limited amount of cracking of the slab concrete is permitted, there may be substantial increases in the permissible gross weight of overload vehicles, provided that they will traverse the bridge infrequently and that they have a large number of axles and wheels per axle. If these conditions are met, the axle weights (125 kN; 28 kips) or equivalent pressure (47 kPa; 2.25 ksf) can be used for rough estimation of the permissible vehicular weights. Through the use of the table provided, it is possible to predict with greater accuracy the effects of overload vehicles on the deck.

Acknowledgments and Disclaimer

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Table 1. Vehicular load levels causing deck cracking

Vehicle No.	Bridge No.	Gross Weight (kN)	Axle Weight (kN)	Equiv. Pressure (kPa)
1	1	538	119	64
1	2	574	128	69
1	3	587	130	70
1	4	405	90	48
1	5	445	99	53
1	6	552	123	66
1	7	405	90	48
1	8	445	99	53
1	9	552	123	66
2	1	476	159	68
2	2	471	157	68
2	3	396	132	57
2	4	325	108	47
2	5	342	114	49
2	6	356	119	51
2	7	325	108	47
2	8	342	114	49
2	9	356	119	51
3	1	507	127	52
3	2	485	121	50
3	3	414	104	42
3	4	351	88	36
3	5	365	91	37
3	6	369	92	38
3	7	351	88	36
3	8	369	92	38
3	9	369	92	38
4	1	512	171	55
4	2	556	185	60
4	3	454	151	49
4	4	516	172	55
4	5	494	165	53
4	6	467	156	50
4	7	512	171	55
4	8	489	163	53
4	9	498	166	54
5	1	534	134	34
5	2	543	136	35
5	3	471	118	30
5	4	552	138	35
5	5	534	134	34
5	6	525	131	34
5	7	547	137	35
5	8	520	130	33
5	9	480	120	31

Table 2. Statistical averaging of load levels causing deck cracking.

Span Length (m)	30.5	21.35	12.2
Average Axle Weight (kN)	126.7	128.5	125
St. Deviation (kN)	31.3	28.7	21
St. Error in the Mean (kN)	8	7	5.4
Average Eqv. Pressure (kPa)	47.7	48.9	48.5
St. Deviation (kPa)	10.5	11.6	12.8
St. Error in the Mean (kPa)	2.8	3	3.3

Figure 1. Plan and cross-section of Bridges 1, 2 and 3 (subscripts indicate bridge numbers; 1 in. = 25.4 mm, 1 ft. = 0.305 m)

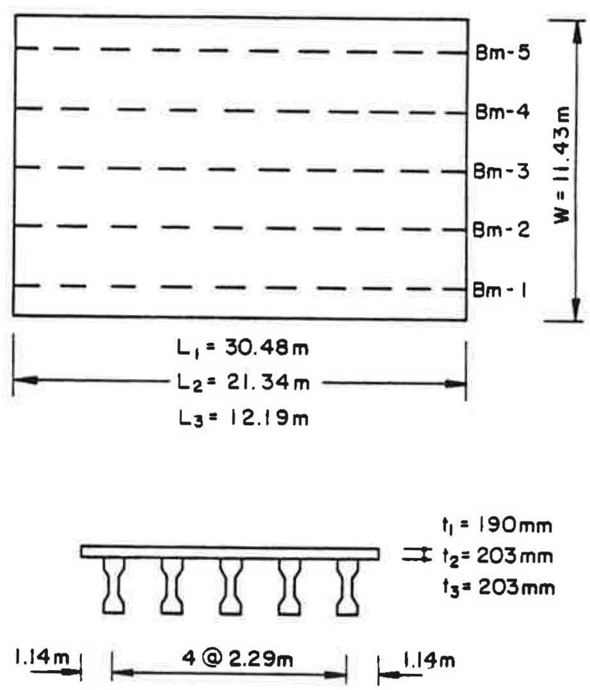

Figure 2. Plan and cross-section of Bridges 4, 5 and 6 (subscripts indicate bridge numbers; 1 in. = 25.4 mm, 1 ft. = 0.305 m)

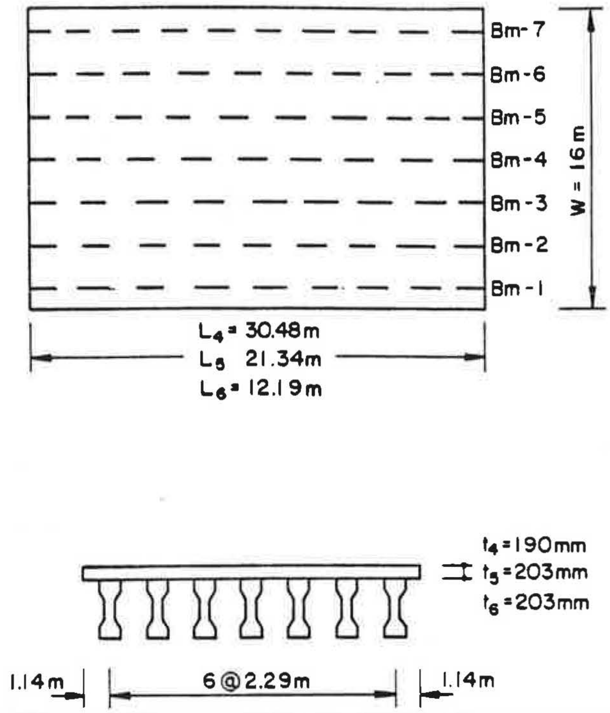

Figure 3. Plan and cross section of Bridges 7, 8 and 9 (subscripts indicate bridge numbers; 1 in. = 25.4 mm, 1 ft. = 0.305 m)

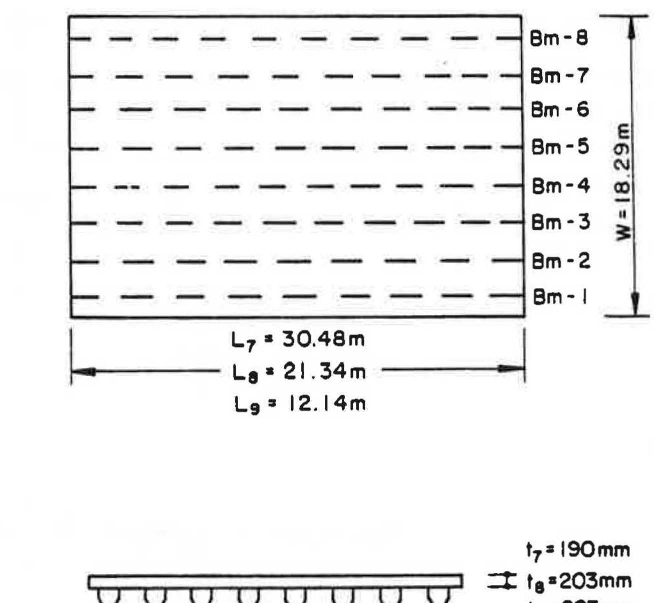

Figure 4. Overload Vehicle No. 1 (1 k = 0.225 kN, 1 in. = 25.4 mm, 1 ft. = 0.305 m)

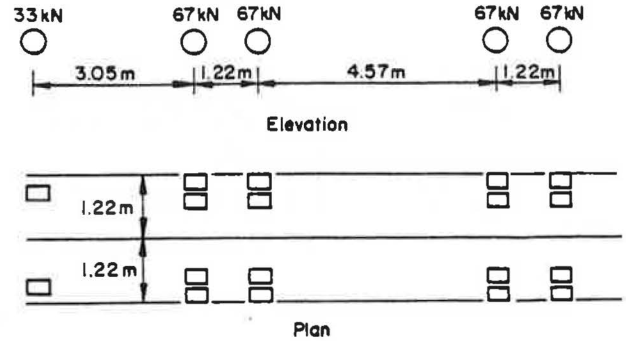

Figure 5. Overload Vehicle No. 2 (1 k = 0.225 kN, 1 in. = 25.4 mm, 1 ft. = 0.305 m)

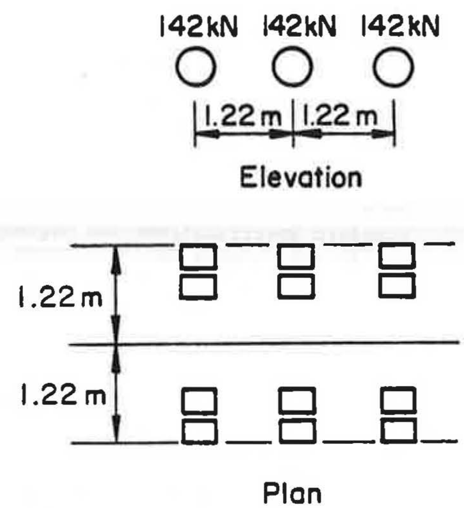

Figure 6. Overload Vehicle No. 3 (1 k = 0.225 kN, 1 in. = 25.4 mm, 1 ft. = 0.305 m)

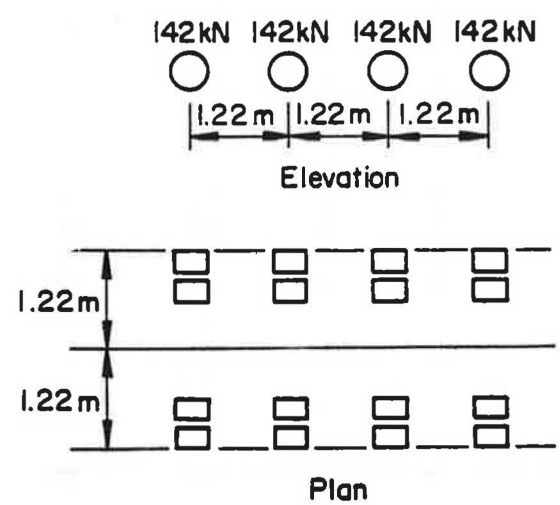

Figure 7. Overload Vehicle No. 4 (1 k = 0.225 kN, 1 in. = 25.4 mm, 1 ft. = 0.305 m)

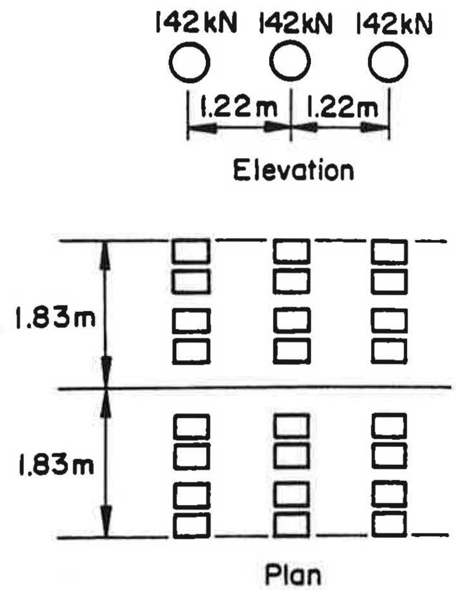

Figure 8. Overload Vehicle No. 5 (1 k = 0.225 kN, 1 in. = 25.4 mm, 1 ft. = 0.305 m)