Technical Path for Reliability Design of Overlying-Buildings Comfort for Wheel-Rail Vibration on Urban Rail-Transit Depots

Wei Huihui[1], Liu Hongliang[2,*], Xiao Yangzhe[2], Zou Kangjing[2]

[1]China Construction Shanghai Design and Research Institute Co., Ltd, Shanghai, 200062, China

[2]College of Urban Construction and Safety Engineering, Shanghai Institute of Technology, Shanghai, 201418, China

*Corresponding author

Keywords: rail traffic; over-track buildings; wheel-rail vibration; comfort; vibration reduction and isolation technology; reliability

Abstract: The frequent complaints from owners regarding the comfort of the cover buildings above urban rail transit vehicle depots appear to be caused by differences in construction conditions across various projects, unreasonable analytical and calculation methods, and discrepancies in testing that lead to distorted results. This results in significant fluctuations in the predicted or evaluated comfort levels of the cover buildings' wheel-rail vibrations. However, at its core, the issue arises from uncertainties in the performance of vibration isolation materials or products, uncertainties in the geometric dimensions involved in the vibration isolation process, uncertainties in the calculation models used to predict the comfort of the cover buildings' wheel-rail vibrations, and uncertainties in the experimental methods and techniques used to evaluate this comfort. Essentially, this is a reliability design issue for the wheel-rail vibration comfort of over-track buildings. The definition of the limit state for the wheel-rail vibration comfort of over-track buildings above rail transit vehicle depots is proposed. A limit state equation is established, consistent with conventional reliability theory for building structures. Based on a technical pathway analysis of the comfort of over-track buildings above rail transit vehicle depots, a unique and innovative approach is taken by shifting the focus of the comfort issue to vibration isolation technologies and measures outside of the over-track buildings themselves. This novel method instantly clarifies and simplifies the highly complex reliability problem of wheel-rail vibration comfort in the over-track buildings. Building on the above, a clear and specific technical pathway for the reliability design of wheel-rail vibration comfort in over-track buildings is proposed, laying a solid foundation for further research into the reliability of wheel-rail vibration comfort in over-track buildings.

1. Introduction

In recent years, China's rail transit business has been rapid development, urban rail transit over-track buildings projects are constructed in large numbers, and the research work related to it is also carried out one after another, and a number of research results have been obtained [1-25].

Research on the comfort of wheel-rail vibration in over-track buildings focuses on two aspects: i. After the completion of the proposed over-track buildings, the internal vibration indexes of the building are measured to evaluate whether the comfort level of the over-track buildings is up to the standard or not [1-2,4-5,7-8,10-15,17-19,22-25]; ii. Using the vibration recordings of the railroad transit under the measured or similar conditions as the loading inputs, a finite element model analysis is completed to predict the comfort level of the proposed over-track buildings [(1-3,5-6,9,9]), and to predict the comfort level of the over-track buildings. Finite element modeling analysis of the rail transit over-track buildings was completed to predict the comfort indicators of the proposed over-track buildings [1-3,5-6,9,11,12,16-17,18-21,25].

Whether using the actual measurement method to evaluate whether the comfort level of the over-track buildings is up to the standard, or using the finite element model analysis to predict the comfort level index of the proposed over-track buildings, there are some problems, for example, there is a representative of Party A pointed out in the 2023 International Railway Transportation Vibration and Noise Reduction Forum of Songjiang that, nowadays, for the over-track buildings project of the rail transit, the comfort level index has been analyzed by modeling at the design stage, and the comfort level index has been measured on the site after the completion of the project. Comfort indicators are up to standard, but still received a lot of complaints about the train traveling noise.

With regard to the above typical problems concerning the comfort of vibration of wheel tracks in over-track buildings, the author believes that they may be caused by the following reasons:

(1) Different rail transit over-track buildings projects, because the vehicle section of the vibration isolation technology, vibration isolation products, vibration isolation links are different, resulting in the same over-track buildings project, built in the A vehicle section, the user on the wheel track vibration is not sensible, while built in the B vehicle section, the user on the wheel track vibration may feel strong.

(2) The analysis and calculation methods are not entirely reasonable. There are many factors affecting the results of analysis and calculation, such as the selection of unit characteristics, unit division, load source, personal modeling ability, and so on. The same over-track buildings project, different people to modeling analysis, may also get the results have obvious differences.

(3) Distortion of results due to bias in testing. Instrumentation of the same type but from different manufacturers can generally be calibrated to control deviations, so these deviations are generally small. The main bias comes from the fact that for the same over-track buildings project, the testing program developed by different people, there are large differences.

The three main reasons can be summarized as the uncertainty in the performance of vibration isolation materials or vibration isolation product technology, the uncertainty in the geometric dimensions involved in the vibration isolation process, the uncertainty in the calculation model for predicting the track-vibration comfort of the over-track buildings, and the uncertainty in the experimental methods and approaches for evaluating the track-vibration comfort of the over-track buildings. In essence, this is a reliability design issue for the track-vibration comfort of the over-track buildings.

This paper takes the reliability design of track-vibration comfort for the over-track buildings as the starting point, defines the limit states of track-vibration comfort for the over-track buildings, establishes a limit states equation consistent with the conventional building structure reliability theory, and finally, based on the technical approach for the comfort of urban rail transit depot over-track buildings, explores the technical path for their reliability design.

2. Limit state of vibration comfort for wheel tracks of over-track buildings

2.1 Presentation and Definition of Comfort limit state

The comfort of wheel-rail vibration of rail transit over-track buildings belongs to the problem of normal use limit states of buildings and structures. The limit states of normal use defined by the current code, in addition to considering the structural durability of the structure, is mainly to consider the subjective feelings of people, such as structural components deflection is too large, cracks are too wide, the wall off the skin, etc., will trigger the discomfort of the human visual senses, and then such as ultra-high-rise building structure under the action of the acceleration of the wind load will trigger the discomfort of the human motor senses, and the vibration of the wheel tracks of the building on top of the rail transit, which is triggered by the discomfort of human auditory senses.

Although the problem of wheel-rail vibration comfort of rail transit over-track buildings belongs to the problem of normal use limit states, the design idea has obvious characteristics. Building structure acceleration, deflection, crack width, wall cracking and peeling and other problems can be solved by adjusting the stiffness of components or structure, material strength level and reinforcement construction measures, while the comfort of rail transit building wheel track vibration, first of all, through a variety of links of vibration damping and isolation measures will be considered through the wheel track vibration and noise energy consumption. Of course, the purpose of vibration damping can be partially achieved by adjusting the stiffness (i.e., thickness) of the floor slab and increasing the number of spacer walls [26].

2.2 Limit state of wheel-rail vibration comfort for over-track buildings Equation establishment

The limit state of wheel-rail vibration comfort for rail transit over-track buildings can still be expressed by the limit states equations of the structure:

$$Z= R - S= 0 \tag{1}$$

However, the connotations and meanings of the symbols in Eq. are different from the familiar structural reliability, where *Z* is the function function, *S* is the wheel-rail vibration action, *R* is the

$$R= r+ [S] \tag{2}$$

where *r* is the vibration acceleration level that can be impaired by all the vibration reduction and isolation links between the track end and the indoor measurement point of the building above the rail transit, and [*S*] is the standard permissible vibration acceleration level, as described in the literature [27].

Obviously, Equation (1) can be presented by the schematic diagram of the limit states equation (Fig. 1). As can be seen from Fig. 1, *Z*> 0 is our desired state, which corresponds to the meaning of the limit states of wheel-rail vibration comfort for the over-track buildings: the vibration induced by the train wheel-rail, after being attenuated by each vibration reduction and isolation link, has a vibration acceleration level no greater than the vibration acceleration level permitted by the association standard T/CECS 1035-2022 [27].

2.3 Proposing the significance of the limit state of wheel-rail vibration comfort for over-track buildings

Since the wheel-rail vibration comfort problem of rail transit over-track buildings can be attributed to the normal-use limit states problem of buildings and structures, and at the same time it can be expressed by the limit states equation of Equation (1) and the schematic diagram of Fig. 1, the wheel-rail vibration comfort problem of over-track buildings can still be researched and designed by using the mature reliability design theory.

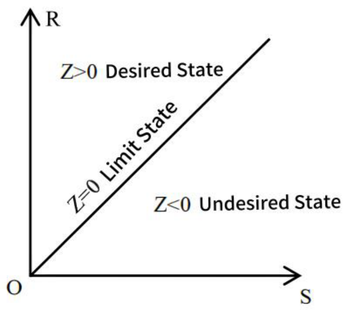

Fig. 1 Diagrammatic sketch of limit state equation

3. Wheel track vibration comfort of over-track buildings Reliability Technical path of design

3.1 Analysis of technical routes

The reliability problem of building structural component level has been very mature from design theory to design method [28], but the reliability problem of complex structural systems still remains in the theoretical stage, and there is an uncrossable gap between design theory and design method.

Theoretically, the existing scholars' modeling and analysis method for the vibration comfort of wheel tracks of over-track buildings can be used as a technical path for the research of vibration comfort and reliability theory, and as long as it is in accordance with the load-resistant mode, it can be used to carry out systematic research on the vibration comfort and reliability theory of wheel tracks of over-track buildings in a systematic way against the mature research methods and means of the structural reliability theory, but, as mentioned before, because the system-based reliability theory is very complex, and it is extremely difficult to realize in complex structure design, so it is not difficult to infer that the modeling and analysis methods of existing scholars on the vibration comfort of wheel tracks of over-track buildings buildings can not be used as a technical path for the research of vibration comfort reliability theory. For this reason, we have to find another way.

From the technical path, the design of wheel-rail vibration comfort of rail transit over-track buildings is firstly the vibration reduction and isolation technology design from the wheel-rail contact to the over-track buildings platform, such as the selection of ballasted track and vibration isolation pads, elastic vibration-damping fasteners, trapezoidal rail sleepers, seamless steel rails, rail dampers, damping wheels, steel spring floating plates, row of piles, ground barriers, vibration isolation grooves, three-dimensional vibration reduction and isolation (vibration) bearings, and so on, followed by the design of the over-track buildings. Vibration isolation technology design, such as increasing the number of partition walls, increasing the thickness of floor slabs, reducing the size and number of overhangs, improving the regularity of the structural plan, and selecting sound and vibration isolation materials, etc. Among them, the design of vibration reduction and isolation technology from the wheel-rail contact to the platform of the over-track buildings is detached from the over-track buildings and has nothing to do with the over-track buildings and the structure. However, if the vibration reduction and isolation measures in this process are done well, then many over-track buildings do not need to take pains in architectural and structural design, and the comfort design is easy to meet the standard. From this point of view, the design technology and vibration reduction and isolation level involved in the vibration reduction and isolation paths prior to the over-track buildings plays an important role in the comfort and reliability of over-track buildings, and can be said to play a decisive role in the current stage of the lack of adequate research on vibration reduction and isolation of the wall of the over-track buildings. It can be said that it plays a decisive role in the current stage where there is a lack of adequate research on vibration isolation of over-track buildings walls. Therefore, the design of comfort reliability for wheel-rail vibration in over-track buildings must first of all take into account the level of vibration damping and isolation outside the over-track buildings. . Substituting such a reliability concept into Equation (1) gives a new but very clear meaning to R and S, i.e.:

(1) S, as the action effect, is the vibration generated by the train wheels in contact with the track, and the vibration generated at the measuring point of the over-track buildings, i.e., the acceleration level, which are highly consistent with each other;

(2) R, as a resisting force, refers to the vibration damping capacity of all vibration damping measures and techniques from the track end to the interior measurement point of the rail transit over-track buildings, which includes the vibration damping capacity of the over-track buildings and its additional damping facilities, and the vibration damping capacity of various damping measures and facilities outside the over-track buildings, the latter of which often plays a decisive role in determining the comfort level of the over-track buildings. The latter often plays a decisive role in the comfort of the over-track buildings. It should be noted that, since the comfort design needs to be compared with the vibration acceleration level allowed by the association standard T/CECS 1035-2022, Eq. (2) incorporates the vibration acceleration level limits into the resistance R. The vibration acceleration level limits are based on the vibration isolation capacity of the over-track buildings.

3.2 Reliability Design Strategy

By 2.1 section is not difficult to deduce, the building wheel track vibration comfort and reliability design, mainly outside the building for the vibration reduction and isolation level design, to seize this point, to seize the essence of things, so that the extremely complex building wheel track vibration comfort and reliability design problems, become relatively simple.

3.3 Technical path for reliability design

(1) Target reliability

As shown in Fig. 2, the rail transit vehicle section is divided into test line, throat area, operation depot and maintenance depot, and each zone has different speeds and frequency of traffic, which affects the comfort of the over-track buildings differently, so the target reliability of each zone will be different.

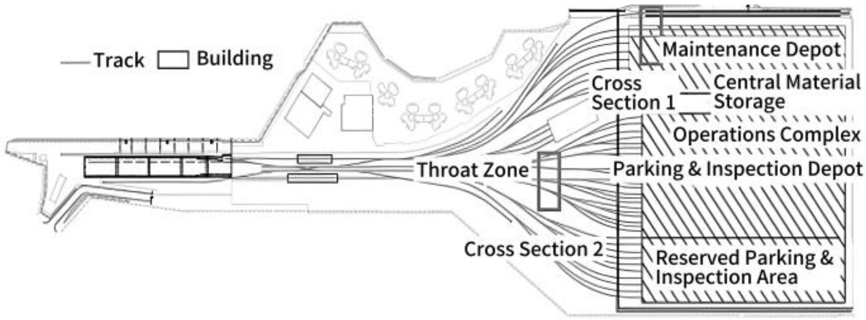

Fig. 2 Sketch of rail-transit traffic depot plan

In Equation (1), to find the target reliability of comfort in each zone, there is only one variable *S* representing the action effect and *R* representing the resistance, where r contains more variables.

There are ballast track and vibration isolation pads, elastic vibration damping fasteners, trapezoidal rail sleepers, seamless rails, rail dampers, damping wheels, steel spring floating plates, row of piles, ground barriers, vibration isolation trenches, and three-dimensional vibration-damping (vibration isolation) bearings ...... are denoted by r_1, r_2, r_3, r_4, r_5), respectively, ... are denoted. Obviously, r_i (i=1, 2, 3, 4, 5 ......) are random variables, they have their own type of probability distribution, through the investigation of statistics, you can obtain their probability distribution function, mean and mean square deviation, respectively, and then the JC method can be used to determine the target reliability β.

Obviously, the $[\beta]$ varies for the test line, throat area, utilization depot and overhaul depot.

(2) Reliability design

The design of wheel-rail vibration comfort reliability for rail transit over-track buildingss can be done by using the calibration method with the following equations:

$$\beta_{\min} \geq [\beta] \tag{3}$$

In the formula, $\beta_{\min}$ indicates that a functional area of the vehicle section in different combinations of vibration isolation technology, vehicle vibration to bring the minimum reliable indicator of the comfort of the over-track building; $[\beta]$ indicates that the comfort of the area in the vehicle vibration to achieve the standard limit value of the target reliable indicator.

4. Summary

Due to the long technical path of vibration reduction and isolation from the rail end to the rail transit over-track building platforms, various factors, such as differences in measures, product processing and manufacturing levels, and material performance, lead to variability in the reliability of equipment and facilities for vibration reduction and isolation. At the same time, there are differences in the professionalism and proficiency of workers' construction techniques. In short, these factors are numerous, making it necessary to treat them as random variables for statistical variability and probability analysis. This will provide the statistical parameters of the random variables needed for the reliability design of wheel-rail vibration comfort in over-track buildings. To this end, the following work is done in this paper:

(1) The definition and significance of the limit states of wheel-rail vibration comfort for the over-track buildings of a railroad car section are presented;

(2) The corresponding limit states equations are established, in which the variables are given a

meaning different from that of conventional structural reliability;

(3) Based on the analysis of the technical path of the comfort of the over-track buildings of the railroad car section, the technology path of the comfort of the over-track buildings is uniquely focused on the vibration reduction and isolation technology and measures outside the over-track buildings, so that the extremely complex problem of the comfort and reliability of the wheel-rail vibration of the over-track buildings is instantly made clear and simple;

(4) On the basis of the above, the technical path for the design of wheel-rail vibration comfort and reliability of over-track buildings is clearly and specifically put forward, which lays a good foundation for in-depth research on wheel-rail vibration comfort and reliability of over-track buildings.

Acknowledgement

Project Information: Science and Technology Research Topics of China State Construction Engineering Corporation Ltd. (Number: CSCEC-2022-Q-59)

References

[1] Xie Weiping, Yuan Kui, Sun Liangming. Train-induced vibration test of metro depot over-track buildings [J]. Journal of Architecture and Civil Engineering, 2020, 37 (03): 99-107.(in Chinese)

[2] Cao Zhigang, Wang Siqi, Xu Yifei, et al. Vibration mitigation mechanism and effect of ballast mats for over-track buildings on metro depot [J]. Journal of Zhejiang University (Engineering Science),2023,57(01):71-80.(in Chinese)

[3] ZHAO Na. Vibration serviceability research on top head estates of subway [D].Hubei: Wuhan University of Technology, 2012.(in Chinese)

[4] Zeng Zemin. Field experimental study on vibration and noise effect induced by train running in metro depot [D]. South China University of Technology, 2015.(in Chinese)

[5] Zou Chao. Research on vibration propagation law and vibration reduction technology of subway vehicle section and over-track buildings [D]. South China University of Technology, 2018. (in Chinese)

[6] ZHENG Hui. research and design application of vibration damping ditch technology in metro depot with upper property development [J]. Railway Stand and Design,2018,62(11):150-154. (in Chinese)

[7] Lin Chujuan,Qi Yuekun,Xing Yi, et al. Propagation law of vibration from test line in metro depot [J].Urban Rapid Rail Transit,2015,28(05):77-81.(in Chinese)

[8] Chao ZOU, Ying C, Zi-Hao HU, et al. Train-induced vibration transmission within over-track buildings in different areas of metro depot [J]. Noise and Vibration Control, 2022,42(06):181-186. (in Chinese)

[9] Wang Ziyu.Field test and simulation analysis on environmental vibration of metro depot[D].East China Jiaotong University, 2018.(in Chinese)

[10] WANG Yimin, ZENG Zemin, ZOU Chao, et al. Experimental investigation into train-induced vibrations of test-line at metro depot [J]. Journal of South China University of Technology (Natural Science Edition), 2014, 42 (12): 1-8. (in Chinese)

[11] Liu Pinyan.Study on train-induced vibration propagation characteristics and vibration isolation effect of utility tunnel in metro depot [D]. China University of Technology,2021. (in Chinese)

[12] Zhou Jie .Experimental study on ambient noise characteristics and control methods on sinking metro depot [D]. South China University of Technology, 2021.(in Chinese)

[13] HE Lei, SONG Rui-xiang, WU Yu-bin, et al. Study on vibration response of upper structure on

throat area of metro depot [J]. China Environmental Protection Industry, 2019(10): 233-236. (in Chinese)

[14] WU Yubin, SONG Ruixiang, HE Lei, et al. Analysis of vibration response characteristics of buildings adjacent to metro depot throat area [J].Urban Mass Transit,2021,24(07):58-62+68. (in Chinese)

[15] HE Lei, Ruixiang Song, Yubin WU, et al. Analysis on actual measurement of train speed influence on the vibration of over-track buildings of metro-depot [J]. Building Structure, 2015, 45(19): 96-99. (in Chinese)

[16] ZHANG Yunlai. Vibration characteristics and prediction analysis of sunken depot and upper building caused by train operation [D]. East China Jiaotong University, 2020. (in Chinese)

[17] Lv Wenting. Analysis of vibration on the roof of the double-decker underground vehicle section of the subway [D].Southwest Jiaotong University Master Degree Thesis, 2019. (in Chinese)

[18] XIE Wei-ping, CHEN Yan-ming, YAO Chun-qiao. Vibration analysis of train depot over-track buildings induced by train load [J]. Journal of Vibration and Shock, 2016, 35(8): 110-115.(in Chinese)

[19] Jizhao LIU, Bolong J. Study on vibration control effects on the metro depot and Over-Track Buildings Using Floating Rail Fasteners [J]. Railway Standard Design,2023,67(8). (in Chinese)

[20] FENG Qingsong, JIANG Xuan , CHENG Gong , et al. Influence of different stiffness combinations of damping fasteners on vibration and noise of upper building of double-deck depot excited by garage inner track [J].Journal of Railway Science & Engineering, 2023, 20(9):3320-3330.

[21] ZHANG Yingchun , ZHANG Shujing , LI Dongxue. Environmental impact analysis of upper cover project in rail transit depot [J]. Railway Energy Saving & Environmental Protection & Occupational Safety and Health,2020,10(05):20-26. (in Chinese)

[22] LIU Tanghui, TU Qinming, LUO Xinwei, et al. Experimental study on vibration of metro depot overhead property Induced by bridge crane running [J]. Mass Transit,2021, (09):127-131. (in Chinese)

[23] CHEN Yan-ming, FENG Qing-song, LIU Qing-jie, et al. Test and analysis of vibration induced by train operation in sinking metro depot service shop [J]. Journal of Vibration, Measurement and Diagnosis, 2021, 41(3): 532-538+623. (in Chinese)

[24] ZHAO Na.Vibration serviceability research on top head estates of subway [D].Hubei:Wuhan University of Technology,2012.(in Chinese)

[25] LI Xiao-lin,TAO, ZHANG Ding-sheng. Study on vibration effects induced by subway train on structures of subway depot cover development [J]. Urban Rapid Rail Transit, 2014, 27(3): 13-17.(in Chinese)

[26] YUAN Kui.Vibration characteristics analysis and vibration isolation study of construction car on top of subway depot [D].Hubei:Wuhan University of Hubei:Wuhan University of Technology,2020.(in Chinese)

[27] China Engineering Construction Standardization Association. T/CECS 1035-2022 Design standard for urban rail transit over-track buildings [S]. Beijing: China Architecture & Building Press, 2022.(in Chinese)

[28] LIU Hong-liang, GAO Jie, SHAO Xin-yan. Reliability study based on new codes of lightweight steel structure [J]. Reliability study based on new codes of lightweight steel structure[J]. Building Structure,2010,40(08):77-82.(in Chinese)