ABSTRACT

The new Chengdu Shuangliu airport is an overlength large-span hybrid structure, with maximum length of 496m and maximum width of 206m. 16 steel arches are supported on RC frame structure. In this paper, time history seismic analysis considering multi-support and multi-dimension effect is carried out. Travelling wave velocity varies from 266m/s to 533m/s. The results from multi-support and multi-dimension seismic analysis have been compared with the results from single-support and multi-dimension analysis, and the significant differences of these results are shown. It is found that the internal force of steel members become smaller when travelling wave effect is considered. The travelling wave effect coefficients of steel members are almost less than 1.2. The internal force along the seismic wave propagation direction of the many 1st RC frame column will increase, but the internal force of the most 1st RC frame column which is perpendicular to wave direction will decrease. The travelling wave effect coefficients of the side column increase from the middle to two sides. Base shear force caused by multi-support excitation is less than that caused by uniform excitation. The reason is that the vibration of structure members is not synchronized when multi-support excitation occurs, so that superposition of the total base shear tends to mutually counterbalance. Adjustment coefficients considering multi-support excitation have been issued for seismic design.
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The new Chengdu Shuangliu airport is an overlength large-span hybrid structure, with maximum length of 496m and maximum width of 206m. 16 steel arches are supported on RC frame structure. In this paper, time history seismic analysis considering multi-support and multi-dimension effect is carried out. Travelling wave velocity varies from 266m/s to 533m/s. The results from multi-support and multi-dimension seismic analysis have been compared with the results from single-support and multi-dimension analysis, and the significant differences of these results are shown. It is found that the internal force of steel members become smaller when travelling wave effect is considered. The travelling wave effect coefficients of steel members are almost less than 1.2. The internal force along the seismic wave propagation direction of the many 1st RC frame column will increase, but the internal force of the most 1st RC frame column which is perpendicular to wave direction will decrease. The travelling wave effect coefficients of the side column increase from the middle to two sides. Base shear force caused by multi-support excitation is less than that caused by uniform excitation. The reason is that the vibration of structure members is not synchronized when multi-support excitation occurs, so that superposition of the total base shear tends to mutually counterbalance. Adjustment coefficients considering multi-support excitation have been issued for seismic design.

1 Introduction to the building

The biggest planar dimensions of the reinforced concrete (RC) frame of Terminal 2 (T2) building of the Chengdu Shuangliu International Airport (CSIA) reaches 496m by 145.6m. The main column net size is 16 m by 12m to 16m. The building has one story underground (some regions do not have basement) and four floors above ground with roof height of 18.9m. The RC frame was prestressed. 32 oblique archs are supported at tips on the roof of the building. Every two oblique archs and the elements of grid structure elements connected to them compose one blade-shaped steel arch shell. Totally there are 16 steel arches with the distance of 508m between two tips. The arch shell is supported with a spacing of 32m and a height of 35.995m. In Fig.1 a three-dimensional analysis model is illustrated. The length of the Terminal 2 hall approaches 500m and the largest width is 206m, which is defined as an super-long large span hybrid structure. Previous study and earthquake engineering practice indicate that the traveling earthquake wave effect is remarkable for such kind of super long complex structure[1~6]. Therefore it is necessary to analyze the structure under multi-support earthquake excitations.

1 Chief Engineer, China Southwest Architectural Design and Research Institute Co., Chengdu, China.
2 Executive Chief Engineer, China Southwest Architectural Design and Research Institute Co., Chengdu, China.
3 Deputy Chief Engineer, China Southwest Architectural Design and Research Institute Co., Chengdu, China.
The existing earthquake response analysis methods under multi-support excitations include the deterministic dynamic analysis method, the random vibration method and the multi-support response spectrum method. The frequently used dynamic analysis method is adopted in this paper. Considering the multi-dimensional effects of ground motions, the analysis was conducted under three dimensional records, that is, two horizontal directions and one vertical direction [7]. The peak ground accelerations (PGA) of earthquake records were adjusted according to the ratio of 1:0.85:0.65[8]. The Sap2000 program was used in the analysis, and four groups of earthquake records were selected, these are: El Centro records, Pujiang records 051PJW (recorded at the 512 Wenchuan Earthquake), Kobe earthquake and one group of artificial records. The PGA of all records is proportionally to 43cm/s² according to the evaluation report of seismic safety for the site of T2 building of the CSIA and the exceedance probability of the PGA level within 50 years is 63%. The acceleration response spectra of these earthquake records in main directions compared to the design spectra of the seismic safety report are shown in Fig. 2 with the PGA set to 43cm/s² and damping ratio of 3%. The vertical earthquake was not considered for the artificial records since no vertical component was provided in the seismic safety report.

The traveling wave effect is taken into account during the dynamic analysis under multi-support excitation. Previous study indicates that the traveling wave effect prevails in the earthquake response of multi-support excitations while the partial interfering effect and local site effect are minor. Hence the response analysis focused on the traveling wave effect, which is performed by inputting the displacement history of each support in Sap2000 program and determining the arrival time of earthquake to each support according to the direction and velocity of earthquake waves. Edward L. Wilson, 2002[9] provides a detailed introduction to the motion equations and theory of response analysis for multi-support excitations. The direct integration method and the Rayleigh damping are used in the dynamic analysis. The difference of arrival time at supports was also set to 0, and it is found that the results of member internal forces are very similar to
those with input acceleration history.

In order to compare the member internal forces under multi-support excitation and uniform excitation, the coefficient of traveling wave effect for member internal forces, $\xi$, is defined as:

$$\xi = \frac{F_{\text{DISPMAX}}}{F_{\text{ACCMAX}}}$$  \hspace{1cm} (1)

Where $F_{\text{DISPMAX}}$ and $F_{\text{ACCMAX}}$ are the maximum member internal forces under multi-support and uniform excitation, respectively. The member internal forces under multi-support excitations are greater than those under uniform excitation when the traveling wave effect coefficient is greater than 1. This type of member is called the overloaded member.

The velocity of earthquake wave has to be determined before the analysis of traveling wave effect. The equivalent shear wave velocity of four hole positions were provided in the geological survey report, which are 274m/s, 340m/s, 302m/s and 310m/s with an average of 307m/s. Referring to the stipulations for Site II in the present Chinese Seismic Code for Design of Buildings (GB50011-2001), four earthquake wave velocity were selected in the analysis in order to study the influence of wave velocity on structural response, which are 266m/s, 307m/s, 400m/s and 533m/s.

The propagation direction of earthquake wave is shown in Fig. 3. This paper focuses on the analysis results under multi-support excitations in the longitudinal direction (X).

![Fig. 3: The planar sketch of structure and the propagation direction of earthquake waves](image)

3 Response analysis results under multi-support excitations

The influence of traveling wave effect on the internal forces of steel and RC structural members is discussed. The law of influence of traveling wave effect some key structural members and the base shear are also put forward.

3.1 Influence of traveling wave effect on steel structures

There are totally 42325 steel members in the Terminal 2 model. The main structural members of a arch are selected for comparison. As is illustrated in Fig.4, there are 366 crucial members in each steel arch.

![Fig. 4: Steel arch, braced frame column and braced steel column](image)
axial and shear forces of steel arch members under El Centro records with velocity of 266m/s, 307 m/s, 400 m/s and 533 m/s, respectively. The horizontal and vertical coordinates are the traveling wave effect coefficient and its distribution frequency, respectively.

Fig. 5: The distribution frequency of traveling wave effect coefficient of steel arches (ELcentro, V=266m/s)

Fig. 6 The distribution frequency of traveling wave effect coefficient of steel arches (ELcentro, V=307m/s)

Fig. 7 The distribution frequency of traveling wave effect coefficient of steel arches (ELcentro, V=400m/s)

Fig. 8 The distribution frequency of traveling wave effect coefficient of steel arches (ELcentro, V=533m/s)

It can be seen in Fig. 5, 6, 7 and 8 that the internal forces of most steel members under El Centro record with velocities varying from 266m/s to 533m/s are less than those under uniform
excitation. The traveling wave effect coefficients of small number of members are greater than 1. Most of them are no greater than 1.2, and only a very few of them are between 1.4 and 1.6. For wave velocity of 266m/s the percentages of members with traveling wave effect coefficient greater than 1 for moments, axial and shear forces are 0.5%, 1.4%, 0.7%, respectively; For wave velocity of 307m/s the percentages of members with traveling wave effect coefficient greater than 1 for moments, axial and shear forces are 0.6%, 1.5%, 0.7%, respectively. For wave velocity of 400m/s the percentages of members with traveling wave effect coefficient greater than 1 for moments, axial and shear forces are 1.0%, 1.6%, 0.8%, respectively. For wave velocity of 533m/s the percentages of members with traveling wave effect coefficient greater than 1 for moments, axial and shear forces are 1.1%, 1.6%, 1.1%, respectively.

The distribution of overload members in arches is further studied. Fig. 9 is distribution and changes with velocity of the percentage of overload members in each arch under El Centro records for moments, axial and shear forces, respectively.

Fig. 9 Percentage of overload members in arches under El Centro record
It can be seen in Fig.9 that most of the overload member is in two side steel arches. The percentage of overload member in steel arch No.13 is the largest while few members are overloaded in intermediate section steel arches. The percentage of overload member generally increases with the increasing of wave velocity. Similarly, the traveling wave effect coefficients of most members under other earthquake records are less than 1. No significant change of overload percentage with increasing of wave velocity is observed. The coefficients of most overload members are less than 1.2. Overload members are mainly in side steel arches.

Fig.10 is the distribution frequency of the traveling wave effect coefficient for axial forces of chord and web members of steel arch No.16 under wave velocity of 307m/s. The horizontal coordinate is the sequential number of steel members from bottom to roof supports. The coefficient varies greatly along the arch and no obvious regularity is found. Generally the coefficient decreases from bottom to roof support.

Fig. 10 Distribution of traveling wave effect coefficient of arch No.16 (V=307m/s)

3.2 Influence of traveling wave effect on RC frames
The influence of traveling wave effect on frame columns is discussed as follows. The local 2 and 3 axis of a frame column is parallel to the global Y and X axis, respectively. The moment
MOMENT2 and shear force SHEAR3 are parallel to the propagation direction of earthquake wave while the moment MOMENT3 and shear force SHEAR2 are perpendicular to the propagation direction. Fig. 11 is the distribution frequency of traveling wave effect coefficient of the moment, axial and shear force of frame column of ground floor under 051PJW record with the velocity of 307m/s.

![Fig. 11 Distribution frequency of traveling wave effect coefficient of frame column of ground floor (051PJW, v=307m/s)](image)

It can be seen in Fig. 11 that the internal forces of first floor column varies greatly under 051PJW record with the velocity of 307m/s. The moment MOMENT2 and shear force SHEAR3 parallel to the propagation direction are generally greater than those of uniform excitation. The percentages are 71.8% for MOMENT2 and 76.2% for SHEAR3. Most of the traveling wave effect coefficient of overload members fluctuates from 1.0 to 2.0. The axial forces of 24.1 percent of total columns are greater than those under uniform excitation. For the moment MOMENT3 and shear force SHEAR2 the percentages are 16.5% and 17.3%, respectively.

The influence of wave velocity on frame columns is remarkable. As is illustrated in Fig.12, the percentage of overloaded columns in first floor varies with different wave velocity of four groups of earthquake records.

![Fig. 12 Percentage of overload columns in first floor with different wave velocities](image)
Fig. 12 Percentage of overload first floor frame columns along with wave velocity

Fig. 12 shows a significant regularity that the percentage of overloaded first floor columns decreases as the wave velocity increases when traveling wave effect is taken into account, with very few exceptions. The percentage under artificial records is the largest while the percentage under Kobe record is smallest, and under 051PJW it is in between them.

3.3 Changes of internal forces of frame columns supporting braced steel arches

As the key member of braced steel arches, the performance of the frame columns supporting arches has direct effect on the performance of arches. Therefore the influence of traveling wave effect on the frame columns of ground and roof floor supporting steel arches is discussed.

Fig. 13 is the distribution frequency of traveling wave effect coefficient of the moment, axial and shear forces of first floor columns along direction X under El Centro record. The horizontal coordinate is the X coordinates of frame columns, and the vertical one is the traveling wave effect coefficient.

Fig. 13 Distribution frequency of traveling wave effect coefficient of internal forces of first floor columns (El Centro record)
Larger at both ends and smaller at intermediate section, the traveling wave effect coefficients of MOMENT2 and SHEAR3 along the propagation direction decreases with the wave velocity increasing. The traveling wave effect coefficients of MOMENT3 and SHEAR2 perpendicular to the propagation direction are larger at two tips and all exceed 1.5, and are generally much less than in the intermediate section. The coefficients of axial forces are less than 1 except for few cases.

Fig.14 is the distribution of traveling wave effect coefficient of internal forces of 4th floor columns connected directly to steel arches.

It can be seen in Fig.14 that the coefficients are all less than 1 as for internal forces of roof floor columns. Magnificent effect of traveling wave effect is found as for the internal forces along propagation direction of most columns on first and second floors. The same applies for forces of first floor columns at two sides perpendicular to propagation direction. The coefficients of third and fourth floor columns are all less than 1.

3.4 **Change of internal forces of braced steel columns**

As another part of key structural members, the earthquake response of steel columns supporting steel arches is also important to structural analysis. These steel columns are mainly under compression. Fig.15 is the distribution frequency along longitudinal direction of airport of
traveling wave effect coefficient of steel columns under different wave velocities and records. Each group of records includes four wave velocities.

![Graphs showing distribution of traveling wave effect coefficient](image)

The coefficients are generally less than 1 with only a few exceptions which are between 1 and 1.2.

### 3.5 Base shear
The difference of base shear between multi-support and uniform excitation is also important. Fig. 16 is the base shear history of direction X and Y under El Centro record with different velocities.

![Graphs showing base shear history](image)

The base shear under uniform excitation is much larger than that of multi-support excitation. The base shear decreases greatly although the internal forces of most first floor columns are greater than those under uniform excitation because of the traveling wave effect. The reason is that the vibration of members under uniform excitation is generally in same phase while it is not under multi-support excitation so that the internal forces are often offset and base shear decreases.

### 4 Conclusions
The conclusions are listed as follows:
1. For the steel structures the internal forces of most members under multi-support excitation are less than those under uniform excitation. The overload members are mostly located at two sides of steel arches and the traveling wave effect coefficients mostly less than 1.2. The number of overload member varies not remarkably with the wave velocity increasing. The coefficients of
axial forces from bottom to frame-supporting bottom of arches decreases along the direction of steel arches.

2. The moment and shear forces of many first and second floor columns along wave propagation direction increase considering multi-support excitation. The traveling wave effect coefficients of overload members are generally between 1 and 2, and the number of overload members decreases with the velocity increasing. The moment and shear force of columns perpendicular to wave propagation direction mostly decreases. The overload member percentage is the under artificial records, larger under 051PJW record and the under Kobe of all earthquake records.

3. The traveling wave effect coefficient of moment MOMENT2 and shear force SHEAR3 of many of the first and second floor columns supporting steel arches are greater than 1, and are larger at two sides while smaller at intermediate section. The coefficients decrease with the velocity increasing. The traveling wave effect coefficient of moment MOMENT3 and shear force SHEAR2 of the first and second floor columns are larger at two sides while generally less than 1 in the middle. The coefficients of axial forces are mostly less than 1. For the third and fourth floor columns the coefficient of internal forces are mostly less than 1 with exception of artificial records.

4. Few of the coefficients for axial forces of steel columns supporting steel arches are greater than 1. Only several coefficients are between 1 and 1.2.

5. The base shear under multi-support excitation is much less than that under uniform excitation. The reason is that the vibration of members is not in the same phase under multi-support excitation and the base shears cancel each other out.

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References


